Triassic lithostratigraphy of the northern North Sea Basin

Kjell-Sigve Lervik

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The Triassic strata of the northern North Sea were initially sub-divided into three formations: the Smith Bank, Skagerrak and Cormorant formations (Deegan & Scull 1977), defined within the informal "Triassic group". The succession was little understood at that time as few wells had drilled into the Triassic red beds. In an attempt to unify UK and Norwegian Triassic and Jurassic lithostratigraphical nomenclature Vollset & Doré (1984) revised the nomenclature, defining a group with three formations - the Hegre Group with the Teist, Lomvi and Lunde formations. The objective of this paper is to establish a gross nomenclature, which covers the entire northern North Sea. A revised Triassic lithostratigraphic chart for the Northern North Sea Basin is presented.

Kjell-Sigve Lervik, Statoil ASA, 4035 Stavanger, e-mail: ksl@Statoil.com

Introduction

It should be unnecessary to state that the geology of the North Sea is independent of political and geographical borders. In spite of this, the Triassic lithostratigraphy of the central and northern North Sea has been subject to such limitations. Previous lithostratigraphical sub-divisions and the naming of the succession have been considered without viewing the basin as a whole. Local sub-divisions within the main basin have been erected. According to international lithostratigraphical rules and recommendations, lithostratigraphical nomenclature shall be applied to a basin as a whole, and not in relation to non-geological borders and boundaries (Hedberg 1976; Salvador 1994).

Erecting general lithostratigraphical nomenclature based on information from local observations has resulted in sub-optimal nomenclature due to the lack of an overall picture of the geological development of the basin. The intention of this paper is to revise existing nomenclature in the light of the overall geological history of the basin as known at present and to establish a gross nomenclature, which covers the entire northern North Sea. Information from all released wells on the Norwegian and British sector has been utilized. Further, information from selected wells from the southern North Sea as well as from the Danish sector has been included.

The Triassic lithostratigraphy of the northern North Sea has been outlined in the following major publications: Deegan & Scull (1977), Vollset & Doré (1984) and Cameron (1993). Neither of the last two publications deals with the entire northern North Sea. Vollset & Doré (1984) treat the northern area of tha Norwegian North Sea (Triassic part approximately between 60 – 62^{o} N), while Cameron (1993) concentrated on the British sector. Numerous recent wells have been drilled into the Triassic, and much new information has been obtained since those papers were published.

The Triassic strata of the northern North Sea were initially subdivided into three formations: Smith Bank, Skagerrak and Cormorant formations defined within the informal "Triassic group" (Deegan & Scull 1977). The succession was poorly understood at that time as few wells had been drilled into the Triassic red beds. In an attempt to unify UK and Norwegian Triassic and Jurassic lithostratigraphical nomenclature Vollset & Doré (1984) revised the nomenclature, defining a group with three formations - the Hegre Group with the Teist, Lomvi and Lunde formations. According to the international lithostratigraphical guide (Salvador 1994), the already defined Cormorant Formation has preference to be upgraded to group level instead of introducing a new name.

Several papers have discussed the Triassic succession of the northern North Sea since Vollset & Doré (1984). Lervik et al. (1989) published additional well data and six lithostratigraphic units were suggested for the Triassic succession including the Statfjord Formation, which extends into the earliest Jurassic.

Most subsequent papers are reviews of previous publications and few present new data, except for Steel & Ryseth (1990) who brought a new concept to the dis-

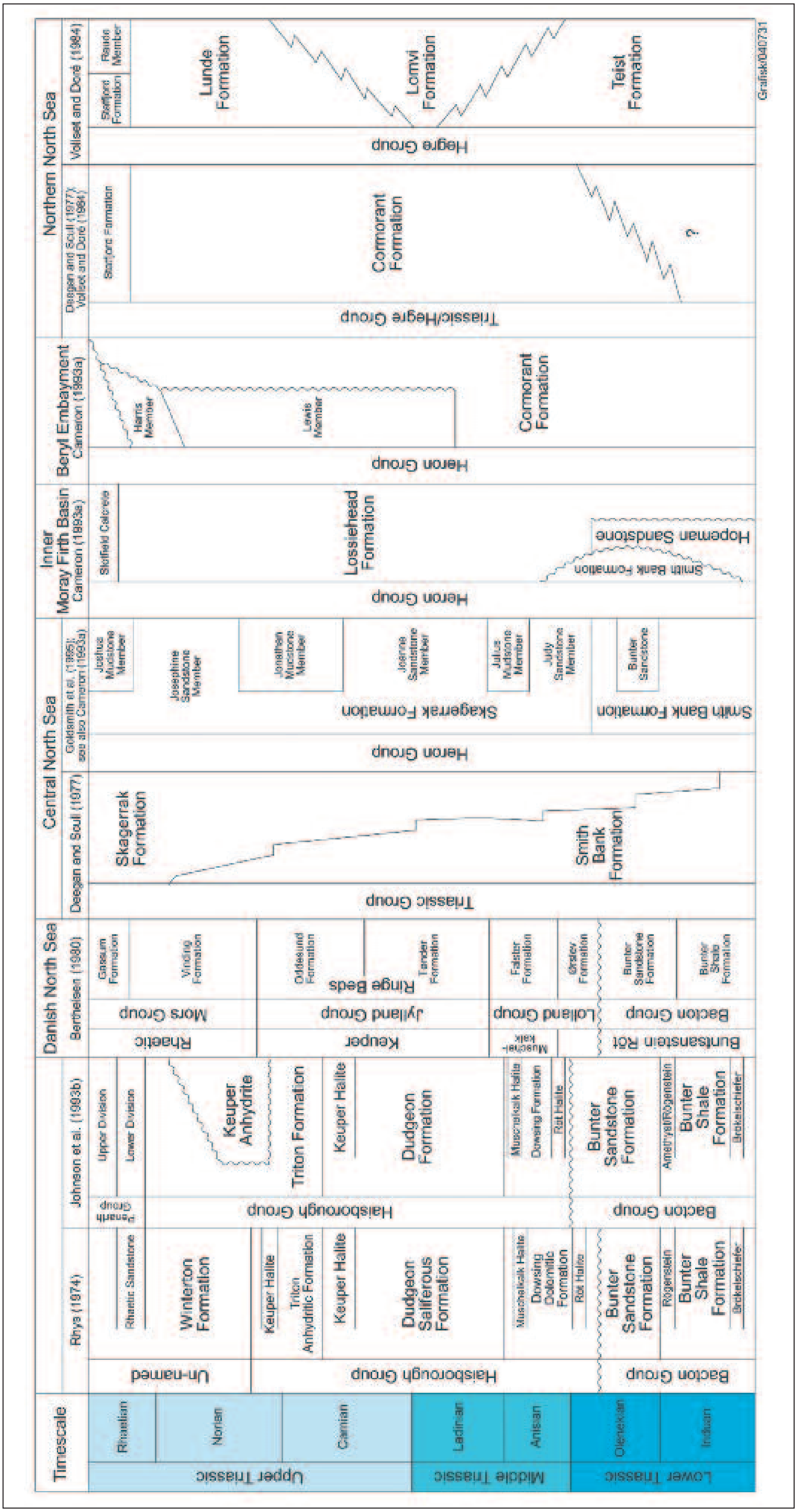

Fig. 1. Previously published Triassic lithostratigraphy of the Southern and Northern North Sea basins (from Goldsmith et al. 2003).

cussion, by proposing a megasequence stratigraphy related to tectonic control rather than using a strictly lithostratigraphic framework for subdividing the Triassic.

The attempt of Vollset & Doré (1984) to unify UK and Norwegian Triassic stratigraphy has not been followed up. Cameron (1993) claimed that some of the lithostratigraphic units could not be recognized in the UK sector, e.g. the Lomvi Formation, although Frostick et al. (1992) reported the Formation from the Beryl Basin: the formation has also been identified in the UK sector in this work. Further, the name of the Hegre Group has been "translated" into English and named the Heron Group. "The geographic component of a name (in this case name of a bird) should not be altered by translation into another language. Stratigraphic units are not limited by international frontiers, and effort should be made to use only a single name for each unit regardless of political boundaries" (Salvador 1994).

Deegan & Scull (1984) defined the Skagerrak and Smith Bank formations in the Central Trough, but did not extend them northwards into the Viking Graben. Johnson et al. (1993) stated that the terms have since been used informally and erroneously. In the type area and in the central North Sea, the Skagerrak Formation overlies the Smith Bank Formation, but in the Viking Graben the Smith Bank Formation is placed stratigraphically above the Skagerrak Formation.

Goldsmith et al. (1995) discussed the stratigraphy of the South Central Trough (UK sector) where the Smith Bank Formation is defined as including the Scythian (Induan-Olenekian) mudstones, whereas Middle Triassic mudstones are included as members of the Skagerrak Formation. This is not in accordance with the original definitions of the Skagerrak and Smith Bank formations made by Deegan & Scull (1977) where the Smith Bank Formation was defined as mudstones distal to the associated Middle Triassic proximal sandstones of the Skagerrak Formation.

A summary of previously defined lithostratigraphical units is shown in Fig.1. This paper discusses the entire northern North Sea. The lithostratigraphic subdivision is related to the dynamic evolution of the basin rather than just to the lithologies. In order to avoid introducing too many names for the same lithostratigraphical unit defined in neighbouring basins, only one new lithostratigraphical unit has been defined. Adjustments to the existing units are proposed.

The wells included in the study are shown on Fig. 2. The cuttings and geophysical logs permit identification of only the major lithostratigraphical units. Therefore minor units, for which biostratigraphical data are necessary to allow correlation have not been discussed. Microfaunal evidence is often very sparse, but where available it has been used to avoid gross miscorrelation. To "compensate" for the frequent lack of microfaunal evidence, wells with a relatively continuous Triassic section have been chosen as the basis for the lithostratigraphical classification. Areas with wells containing only relatively small intervals or discontinuous Triassic successions have not been included in this discussion. Wells from southern part of the British continental shelf have not been included, as information from Cameron (1993) has been incorporated. Wells from the southern part of the Norwegian continental shelf have not been included, as only few wells have penetrated limited unassigned Triassic strata. Confidence in any lithostratigraphy from this part of the shelf must be low. Further wells and information are needed for erection of a reliable lithostratigraphy.

Basin development

The Triassic basin configuration of the northern North Sea has a tectonic history, which started at least as early as Devonian time (Valle et al. 2002). The oldest remnant of sediment infill in the Hornelen Basin onshore Norway (Maehle et al. 1977) represents the first response to break-up of the area, which, after several extensions phases, resulted in the northern North Sea failed arm system, a system which developed in connection with, and was influenced by the overall tectonic break up of the north American Plate from the European Plate.

In addition to outcrops onshore Norway (Hornelen Basin and others), Devonian sediments have been penetrated on the Utsira High (Færseth 1996) and the East Shetland Platform (Lervik et al. 1989) as well as in the Unst Basin (Johns & Andrews 1985), indicating that the northern North Sea was a basinal area in Devonian time. Few wells have penetrated Devonian strata and very little has been done to understand the depositional regime of the Devonian sediments. Where cored, the succession often shows conglomerates or pebbly sandstones reflecting sedimentation at a relatively early stage of basin development. Extensive erosion, >400m on the Utsira High (Færseth 1996), characterises the Devonian succession.

Permian sediments are restricted to the northern Permian Basin in the south and Unst Basin in the west. Permian sediments have not been penetrated in the northern and eastern parts of the basin, indicating erosion or non-deposition during Permian time.

The development of the northern North Sea during Permian time has been disputed (Ziegler 1975, 1982; Badley et al. 1988; Thorne & Watts 1989). Frostick et al. (1992) & Ormaasen et al. (1980) discussed the Per-

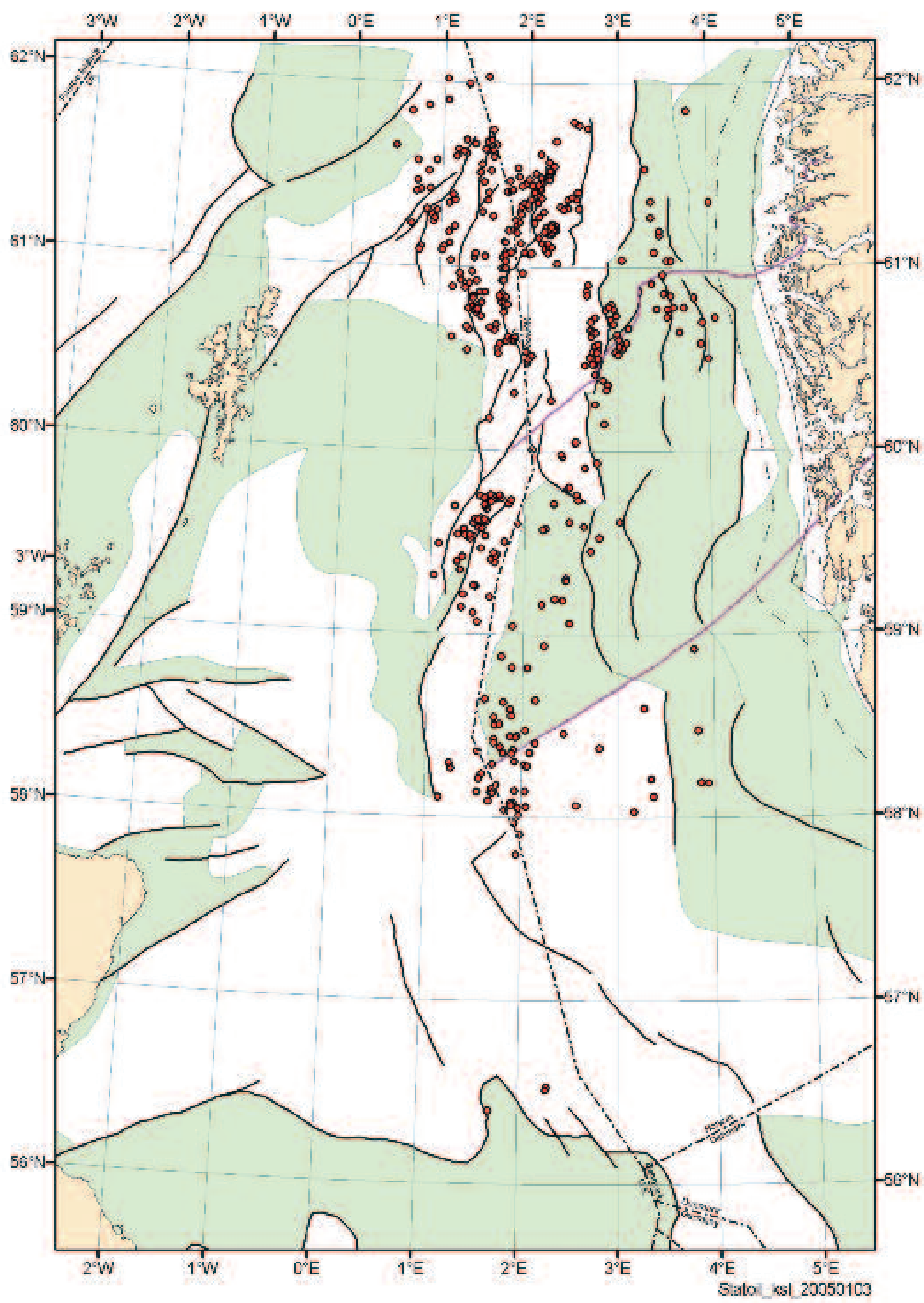

Fig. 2. Wells of Triassic strata which have been included in this study.

mian as a period of tectonically quiet conditions. Taylor (1981) observed abrupt changes of thickness in the Zechstein facies in the central and northern North Sea, and concluded that significant vertical relative movements were taking place during deposition. The idea of Fisher & Mudge (1990) who envisaged a wider depositional area across the Viking Graben, including the present day East Shetland Platform, Unst Basin as well as the East and West Fair Isle basins during the Late Permian, is the most plausible based on available data. The Permian succession is, however, difficult to restore due to later Mesozoic subsidence and Tertiary inversion. Also the difficulty in determining the Permian-Triassic boundary complicates our understanding. Although maximum thicknesses are not possible to determine, as the base of the Permian is not imaged on seismic sections, BGS HMSO, 1993 report several hundred meters of Permian sediments both in the Beryl Basin and in the Magnus Trough.

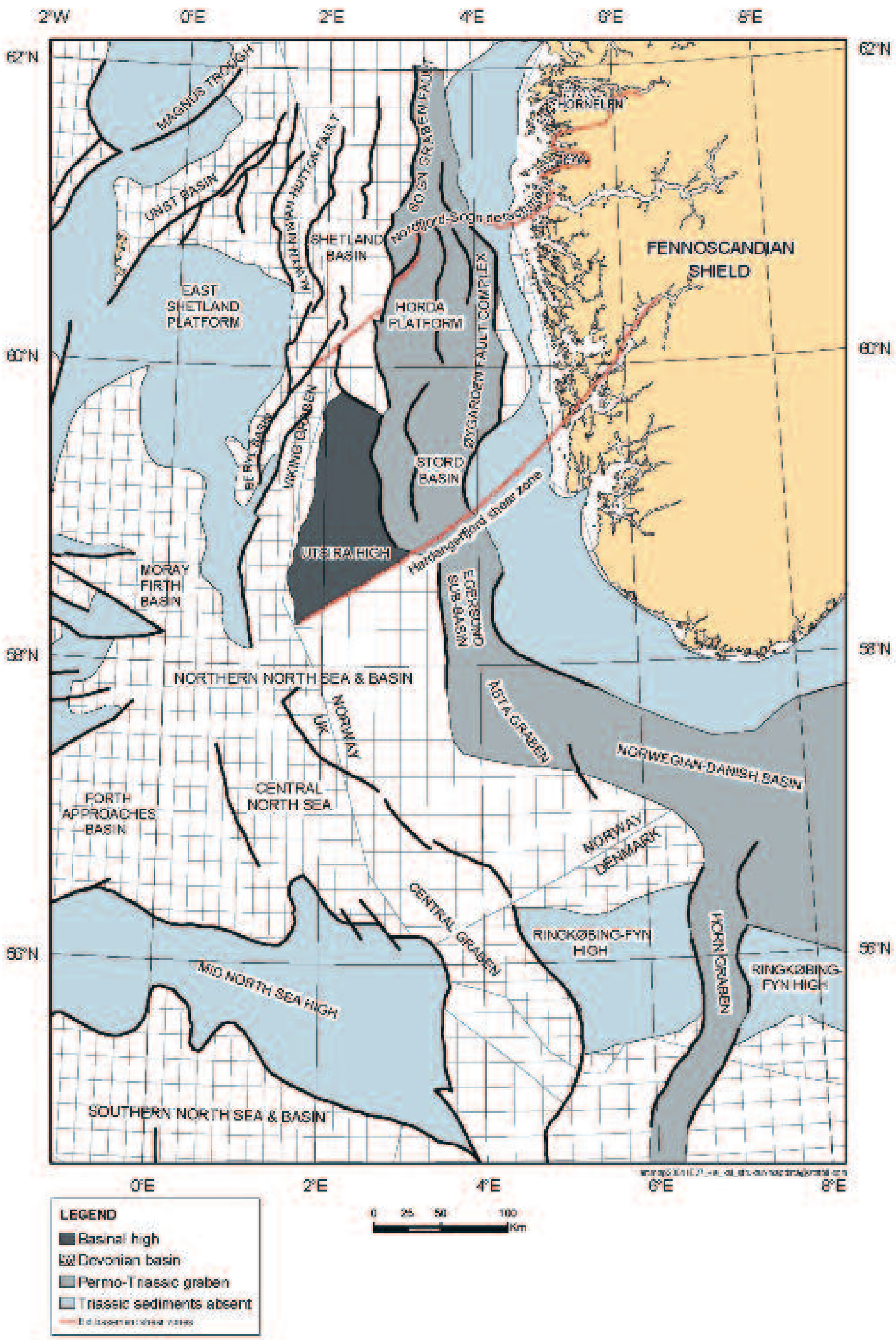

Fig. 3. Structural element map of the central and northern North Sea. The map is based on Bertelsen (1980); Cameron (1993); Færseth (1996) and Fisher & Mudge (1998).

Deposition of salt reflects the presence of the sea in a basin of restricted circulation. The restricted circulation is interpreted to have prevailed until the tectonic pulse of Griensbachian age. A similar extension phase has been reported from East Greenland (Seidler 2001).

The absence of Permian sediments in the northern part of the northern North Sea indicates that the graben developed mainly from the Griensbachian and onwards. The Middle Permian tectonic event recognised in East Greenland and in the Arctic (Bugge et al. 2002) may, although not directly shown by the evidence from the North Sea, have contributed to the development of the N-S trending graben pattern. N-S trending dykes along the present west coast of Norway (Valle et al. 2002) indicate that the basin configuration had been initiated at least in Devonian time. The presence of Scythian (Induan-Olenekian) sediments in wells in the graben along the present coast of Norway shows that enough differential subsidence had occurred to start the trapping of sediments in the graben in the Early Triassic.

The Early Triassic extensional phase dramatically

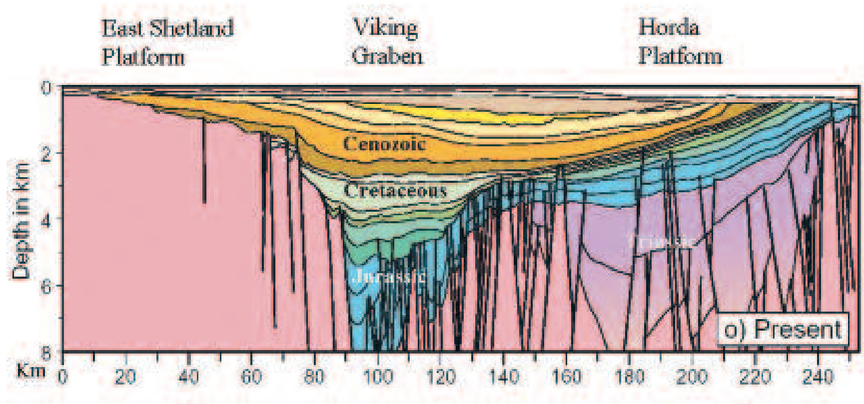

Fig. 4. Cross section showing Triassic infill of the Horda Platform and the Viking Graben (From Kjennerud et al. 2001).

changed the basin configuration of the northern North Sea. The N-S-trending pattern of the graben system became visible, the termination of restricted seawater circulation caused an end to salt deposition and silicate clastic deposition became dominant due to the uplift of the Fennoscandian Shield. Zeck et al. (1988) suggested that uplift of the Fennoscandian Shield and its erosion may have started at the beginning of the Mesozoic. It is further concluded that the clastic material of the Triassic sedimentary basins in the Norwegian-Danish Basin was at least in part derived from the Palaeozoic cover of the Fennoscandian Shield.

The wide depositional area, which prevailed across the entire northern North Sea during Late Permian time now became restricted to a major basin area along the present coast of Norway. The Early Triassic extensional phase resulted in a main rift below the western part of the Horda Platform (Vialli 1988; Færseth 1996). This rift continued further south through the Åsta Graben (Færseth 1996) and the Horn Graben (Olsen 1983; Ramberg & Morgan 1984; Lervik et al. 1989). Extensive thicknesses of Permian Zechstein Group deposits were deposited in the Norwegian – Danish Basin as part of the northern Permian Basin already subsided in pre-Triassic time. The younging of the rift northwards, where Early Triassic sediments (Scytian-Anisian) are reported by Lervik et al. (1989) in well NO 31/6-1, suggests that the rift development was part of the break-up of the Laurasian plate as spreading increased northwards through time.

The main Triassic extension is associated with a north – trending, fault-bounded depression zone 130-150 km wide, with the Øygarden Fault Complex forming the eastern margin of the basin (Færseth 1996) (Fig. 3). The Øygarden Fault Complex continues further south and marks the northern limit of the Norwegian – Danish Basin. Olsen (1983) reported extensive thicknesses of Permian and Triassic sediments in the Norwegian – Danish Basin indicating that this sub-basin was part of the North Sea Triassic basin system. Kjennerud et al. (2001) confirmed the continuation of this structural depression along the present Norwegian coast (Fig. 4). The earliest infill of the depression is thought to be Triassic or older (Kjennerud, pers. comm.).

North of 61° N the structural pattern in the east is controlled by the east-dipping Sogn Graben fault (Færseth 1996). Steel & Ryseth (1990) defined the Alwyn – Ninian – Hutton alignment as the western limit of thick Triassic sediments. Odinsen et al. (2000) defined the Øygarden Fault Zone as the eastern limit of the rift system and the Alwyn – Ninian – Hutton alignment and the East Shetland Platform as the western limit. This is in agreement with the stratigraphy observed in the area. The Lower Triassic succession is present east of the Alwyn – Ninian – Hutton alignment, but not west of it (Lervik et al. 1989).

North of 62° N the structural picture is not clear due to lack of data. Doré (1991) discussed the Hitra Fault Complex as an important feature of the gross structural pattern. This feature may define the northern limit of the north-south trending structural pattern in the North Sea.

Seismic data have been considered to be inadequate for imaging the geometry of the Triassic succession in the southern part of the Jurassic Viking Graben (Færseth 1996). Odinson et al. (2000) have come to a similar conclusion. There are no wells in this area, which allow dating of the Early Triassic section.

Presence of thin Zechstein salt in the south of the Beryl Basin, Frostick et al. (1992) suggest that the area was basinal already in Permian time. Extensive erosion of the strata on the East Shetland Platform in post-Triassic time makes it impossible to decide if Permian sediments were deposited on the East Shetland Platform. Hence, discussion of when the western limit of the Beryl Basin originated is inconclusive. According to Frostick et al. (1992), the western limit of the Beryl

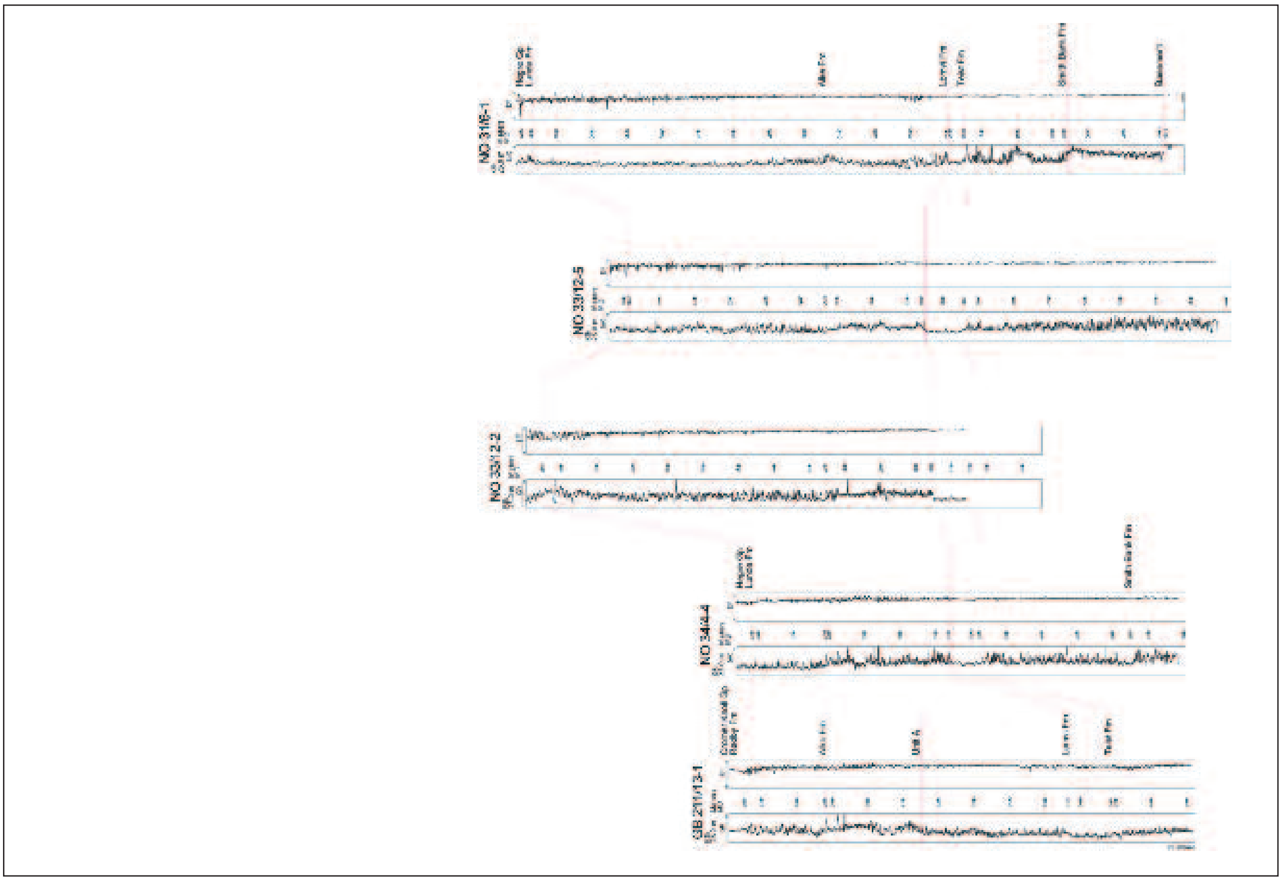

Fig. 5a. Triassic successions from the northern part of the northern North Sea.

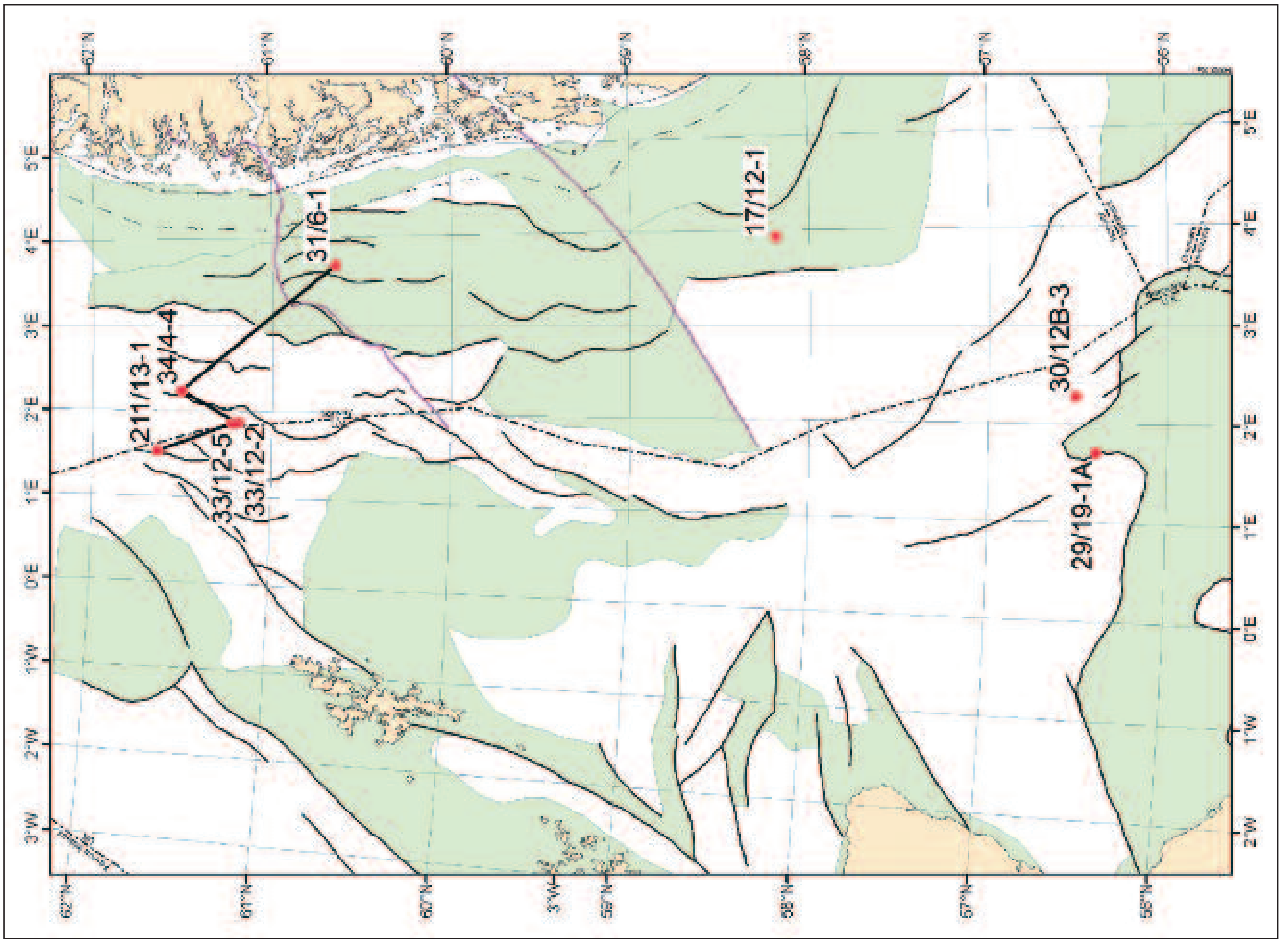

Fig. 5b. Location of wells of figure 5a.

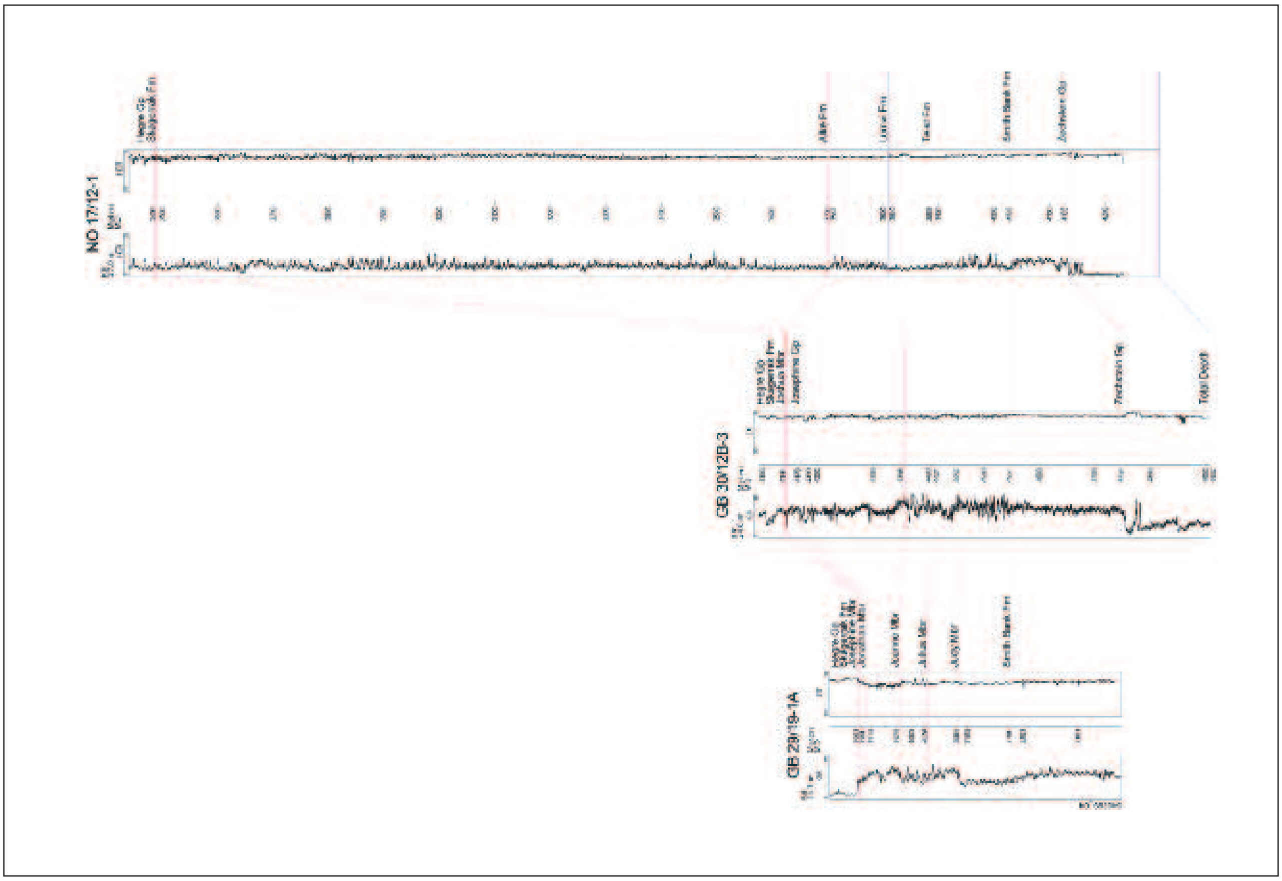

Fig. 6a. Triassic successions from the southern part of the northern North Sea.

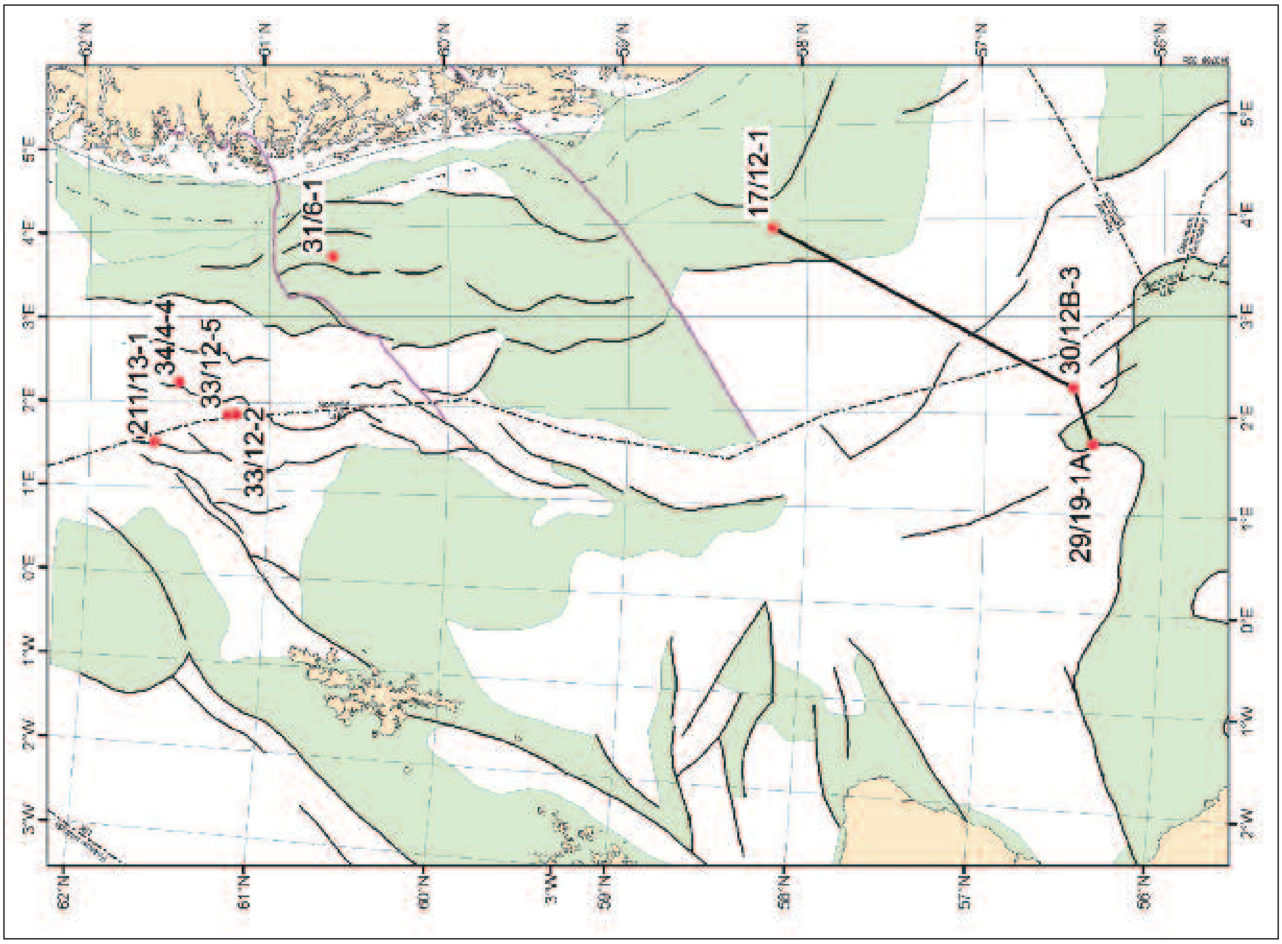

Fig. 6b. Location of wells of figure 6a.

Basin was initiated in Early Triassic time and was probably a southward continuation of the East Shetland Fault.

Based on basin infill patterns, the same authors postulated a phase of fault activity during the Early Triassic followed by a post – rift phase of thermal subsidence. Post Permo – Triassic subsidence had not ended when Jurassic rifting started (Giltner 1987; Gabrielsen et al. 1990; Roberts et al. 1995) and according to Odinson et al. (2000) the subsidence associated with the Permo – Triassic stretching was generally greater than that associated with the Jurassic stretching.

The present Utsira High was probably a topographic high during the Triassic (Steel & Ryseth 1990). Færseth (1996) explained the thinning of Triassic strata to the east of the High to be the result of crustal thinning as well as the effect of Jurassic – Early Cretaceous erosion. The area south of 59° N has been subject to subsidence at least from Permian time as reflected by the presence of the Zechstein Group succession.

Triassic Lithostratigraphy

New lithostratigraphic unit: Alke Formation

Two mudstone formations have previously been defined within the Triassic succession in the North Sea - the Early Triassic Bunter Shale Formation defined by Rhys (1974) in the southern North Sea and the Smith Bank Formation defined by Deegan & Scull (1977) in the northern North Sea. The latter, as originally defined, spans the entire Triassic interval. The relationship between the Bunter Shale Formation and the Smith Bank Formation has through time not been clear.

The presence of two mudstone units in the Triassic succession shown in well NO 34/4-4 and in the composite succession of wells NO 31/6-1 and NO 33/12-5 (Fig. 5), being located in the proximal part of depositional systems, suggests that the Triassic in the northern North Sea had two main phases of mudstone deposition. Distally from the proximal sandstones, there will be no intervening sandstone between the two successions of mudstone. This resulted in a continuous succession of mudstone throughout the entire Triassic, as reflected by the Smith Bank Formation, as defined by Deegan & Scull (1977).

Although Brennand (1975) suggested the presence of the Bunter Shale Formation north of the Mid North Sea High, Deegan & Scull (1977) chose not to correlate existing nomenclature from the southern North Sea and introduced the Smith Bank Formation in the northern North Sea. Deegan & Scull (1977) originally defined the age of the Smith Bank Formation to be Early to possibly Late Triassic, and at the same time stated that, westward from its type well, the Skagerrak Formation interdigitates with, and progrades over the associated claystone unit of the Smith Bank Formation. This implies that the Smith Bank Formation, as originally defined, is time equivalent with the Skagerrak Formation, which was dated as Middle and Late Triassic and possibly Early Triassic. No Triassic sand depositional system older than the Skagerrak Formation was known in the proximal eastern areas.

Bertelsen (1980) discussed the Smith Bank Formation of the Norwegian-Danish Basin as probably of late Late Permian to Early Triassic (Scythian (Induan-Olenekian)) age, thus corresponding to the lower part of the Bunter Shale Formation. He further stated that, to the south, the Smith Bank Formation seems to continue into the Bunter Shale Formation, from which it is not readily distinguished. Bertelsen (1980) also interpreted the Skagerrak Formation as grading downwards and distally into the pelitic Smith Bank Formation.

Goldsmith et al. (1995) revised the Smith Bank Formation to be restricted only to Scythian (Induan-Olenekian) mudstones. Work by Goldsmith et al. (1995) has shown that the Smith Bank Formation is found to be not younger than Early Triassic (pers. com. P. v. Veen). The Smith Bank Formation should not, according to these observations, be equivalent to the Skagerrak Formation as suggested by Deegan & Scull (1977). Goldsmith et al. (1995) introduced a separate mudstone members within the Skagerrak Formation.

As mentioned above, the Triassic succession in the area close to the Fennoscandian Shield, shows two mudstone intervals - one of Early Triassic age and one of Middle Triassic age. In the area to the west of the sandstones of the Skagerrak Formation - where the Smith Bank Formation was originally defined - there is a continuous succession of mudstones throughout the entire Triassic interval. Well GB 33/12B-3 (Fig. 6) shows that the Triassic interval in the distal part of the basin can be subdivided into two mudstone-dominated successions. In well GB 33/12B-3 Goldsmith et al. (1995) used the Skagerrak Formation for the upper part of the Triassic interval, but due to the mudstone-dominated character of the lithology, it would have been rational to define this interval as the Alke Formation (Fig. 6). It might be questioned if the work by Goldsmith et al. (1995) is a sequence stratigraphic sub-division rather than a lithostratigraphic subdivision.

The Alke Formation is here introduced to represent the second phase of mudstone deposition in addition to the first phase Early Triassic Smith Bank Formation.

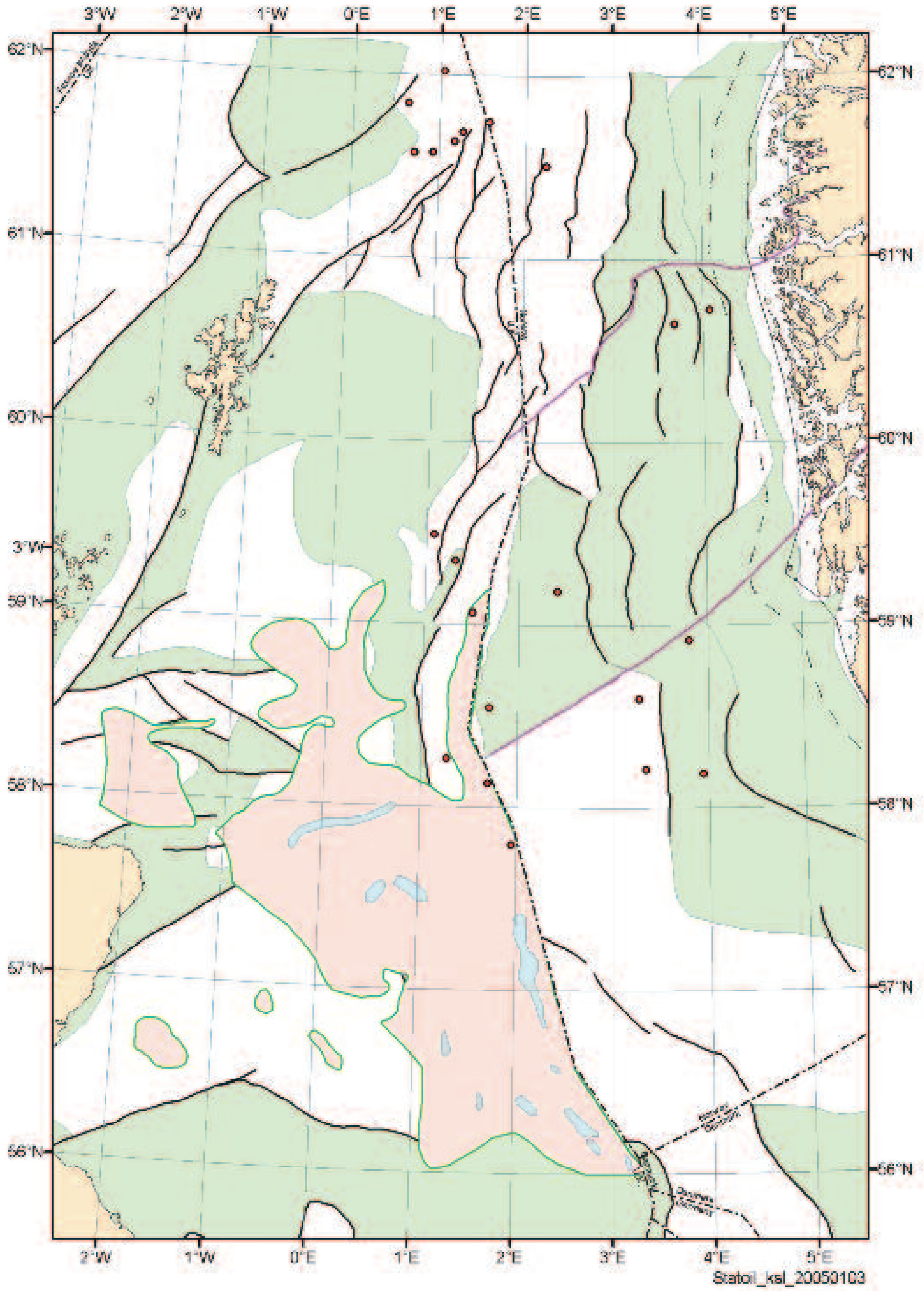

Fig. 7. Distribution of the Smith Bank Formation. The pink outline is from Cameron (1993) and shows the distribution of the Smith Bank in UK.

Bacton Group

The Bacton Group was formally defined by Rhys (1974) for the series earlier designated as the Lower and Middle Bunter (Buntsandstein) in the Southern North Sea Basin. Bertelsen (1980) found lithologies and log motifs similar to those of the Bacton Group of Rhys (1974) in wells in southern and central Denmark and introduced the term in the Danish lithostratigraphic nomenclature. The Group consists of a lower pelitic formation, the Bunter Shale Formation, and an upper arenaceous formation, the Bunter Sandstone Formation.

The Group is present in the Norwegian-Danish Basin (Bertelsen 1980), which is part of the northern North Sea. It is therefore natural to include the Group in the northern North Sea nomenclature. How far north the group should be extended is however, uncertain. The Bunter Shale Formation equivalent (Smith Bank Formation) is present as far north as the northern Viking Graben. The Bunter Sandstone Formation is replaced by the Teist and Lomvi formations of the Hegre Group north of the undrilled Stord Basin (Vollset & Doré 1984). There is definitely a difference in the depositional pattern from the Germano-type Facies Province (Bacton Group) to the northernmost part of the North Sea (Hegre Group). Bertelsen (1980) defined the transition zone towards the Germano-type Facies Province in the central part of the Danish Sub-basin. The northern part of the Norwegian Danish Basin and areas further north are, as opposed to areas further south and west, largely affected by deposition from the Fennoscandian Shield. It is therefore logical to use the Germanic nomenclature south of the transition zone defined by Bertelsen (1980) and the northern North Sea nomenclature north of this zone.

According to the international lithostratigraphic guide (Salvador 1994), the same name should not be used for two different lithostratigraphic units: Bunter Shale Formation and Bunter Sandstone Formation. In addition it is preferable not to use both a lithologic term (shale, sandstone) and a unit term in the name of a lithostratigraphic unit. The Bunter Shale Formation and Bunter Sandstone Formation are defined in the Southern North Sea Basin, and as this paper deals with the Northern North Sea Basin, it is not within the scope of this work to revise the lithostratigraphy erected in the Southern North Sea Basin. It is, however, recommended that those two units should not be adopted in the lithostratigraphy of the Northern North Sea Basin.

Some of the earliest wells on the Norwegian continental shelf were drilled in the northern part of the Norwegian Danish Basin and Germanic nomenclature (Bacton Group) has been used as lithostratigraphic nomenclature on the completion log of the wells. The lithostrati-graphic nomenclature by Deegan & Scull (1977) terminated the use of Germanic nomenclature in the northern North Sea except in the southern part of the Norwegian-Danish Basin.

The Bunter Shale and Bunter Sandstone formations are both formally defined by Bertelsen (1980) in the Danish lithostratigraphic nomenclature. It is therefore no need to describe the units here.

Bunter Shale Formation

The Bunter Shale Formation, consisting of mudstone and shale, was formally defined by Rhys (1974), with well GB 49/21-2 in the Southern North Sea Basin as the type section. The formation overlies the Zechstein Group and is overlain by the sandstones of the Bunter Sandstone Formation. Rhys (1974) suggested that the lower part of the Bunter Shale Formation is likely to be of Permian age.

No direct evidence for the age of the Bunter Shale Formation has been obtained in the Southern North Sea Basin, where it is everywhere barren of sporomorphs (Brennand 1975). North of the Mid North Sea High comparable lithologies have, however, yielded a earliest Scythian (Induan-Olenekian) flora in several wells. A single specimen suggested that the red mudstone facies persisted into the Anisian or even later (Geiger & Hopping 1968; Visscher & Commissaris 1968). Smith & Warrington (1971) report a agediagnostic Late Scythian (Induan-Olenekian) specimen near the top of the 274 m thick unit of red mudstones in well GB 21/26-1D.

Rasmussen (1974) reported unfossiliferous red-brown claystone with some anhydrite and a basal siltstone from the offshore Danish wells B-1 and D-1. Those successions mimic the transition from the underlying Permian Zechstein in the type well of the Bunter Shale Formation, and were interpreted by Brennand (1975) to represent Bunter Shale equivalents.

The distribution of the Bunter Shale Formation in the Northern North Sea Basin is defined by Bertelsen (1980) and is restricted to the southern part of the Norwegian-Danish Basin.

Bunter Sandstone Formation

In the southern North Sea there was one major sand-input event in the Triassic – the Bunter Sandstone Formation. The Bunter Sandstone Formation was formally defined by Rhys (1974) with well GB 49/21-2 in the Southern North Sea Basin as type section. Bertelsen (1980) defined the Bunter Sandstone Formation onshore Denmark and in the Norwegian-Danish Basin, and concluded that it coalesces to the north with the Skagerrak Formation in the Norwegian sector. Bertelsen (1980) stated that the sand content of the Bunter Sandstone Formation in the Danish southern Central Trough is very low, and explained this as a function of the distal position of the area, far from the southerly source of the Bunter Sandstone of the Southern North Sea Basin (Brennand 1975) and far from the source of the Norwegian-Danish Basin. This agrees with the idea proposed in this paper, that there is a continuous succession of mudstone through the entire Triassic in the central part of the Northern North Sea Basin - most distally from the basin margin sand input.

The Bunter Sandstone Formation has been observed only to a limited extent north of the Mid North Sea High as few wells have penetrated the Lower Triassic sandstones. Where penetrated, the sandstones have been assigned to the Skagerrak Formation. In general, it is very speculative to define the Bunter Sandstone Formation when only minor parts of the Triassic succession are present due to lack of age diagnostic flora. It is necessary to have penetrated a rather complete lithostratigraphic succession with under- and overlying lithostratigraphic units in order to recognize the Bunter

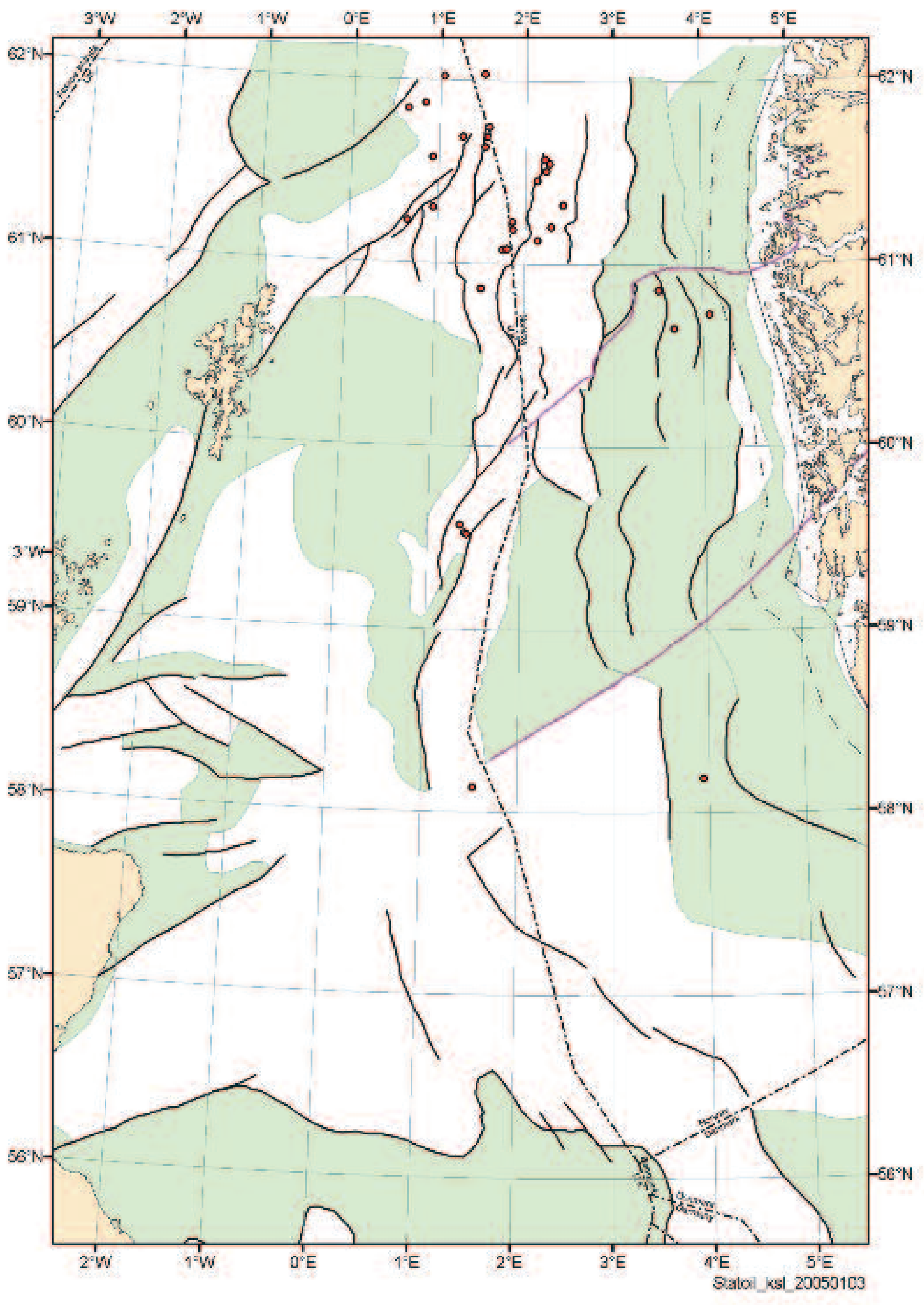

Fig. 8. Distribution of the Teist Formation.

Sandstone Formation within the overall succession. Bunter Sandstone Formation successions penetrated in the Norwegian sector of the Norwegian-Danish Basin have been misinterpreted as the Skagerrak Formation for the reasons mentioned above. There is a general understanding that the Southern North Sea lithostratigraphic nomenclature should not be used in the Northern North Sea Basin because these two subbasins underwent different developments. However, Jakobsson et al. (1980) used the southern North Sea nomenclature by defining the lower part of NO well 17/12-1 as belonging to the Bunter system. On the contrary, the lowermost mudstone interval was correlated to northern North Sea mudstones of the Smith Bank Formation rather than to the Bunter Shale Formation.

Bertelsen (1980) defined the Bunter Sandstone Formation to be present in the Norwegian-Danish Basin south of the transition zone of Germanic nomenclature.

The definition of Deegan & Scull (1977) is not very clear north of this transition zone. The sandstones of the Skagerrak Formation were originally defined as deposited in the Middle and Late Triassic. No lithostratigraphical unit was defined to cover any sandstone deposits of Early Triassic age, equivalent to the Bunter Sandstone Formation. The lack of such a unit caused sandstones of Early Triassic age in this area to be defined as the Skagerrak Formation, though the sandstones did not correspond to the original age given to the Skagerrak Formation.

Teist and Lomvi formations nomenclature should be defined between the Stord Basin and the Ringkøbing-Fyn High instead of using Germano-type nomenclature. If it is impossible to define which of the formations the succession belongs to, it should be defined as unassigned Hegre Group strata. This is in accordance with a similar situation in the northernmost part of the northern North Sea in UK waters.

Hegre Group

In the southern North Sea, the Triassic is, according to Brennand (1975), divisible into two lithostratigraphic groups, a lower one characterized by alternation of mudstones and sandstones and an upper one in which cyclic repetitions of clay and evaporites prevail.
Deposition was in two phases:
1) initial clastic deposition (Bacton Group)
2) subsequent, fine-grained cyclical deposits of mudstones and evaporites of the Haisborough Group and Win-terton Formation.

In the northern North Sea a similar two phase development, but with different lithologies in the second phase, is observed. The stratigraphy of the first phase is similar in the southern part of the northern North Sea (Fig. 12). In the northern part, however, it shows a different pattern. There is a similar transition from mudstones of the Smith Bank Formation to sandstones above, but the section equivalent to the Bunter Sandstone Formation is here represented by two formations – The Teist and Lomvi formations, both defined by Vollset & Doré (1984). The Teist Formation has not been formally defined as it was claimed that its base was not drilled at the time of definition. The base of the Teist Formation was, however, upon definition, penetrated in well NO 33/5-1 at depth 3800m. The Teist Formation is formally defined in this paper (Appendix 1).

Further, the Lunde Formation has been revised. Vollset & Doré (1984) suggested that the lower mudstone section of the Formation should be separated and assigned formation status. This succession is here designated as the Alke Formation.

Vollset & Doré (1984) indicated that the Hegre Group is present in the entire northern North Sea area. Its unclear relationship to the Triassic units defined to the south by Deegan & Scull (1977), led to their recommendation that the Hegre Group should only be used in the area north of 60 degrees north. The Hegre Group is here revised to include the Triassic stratigraphy of the entire northern North Sea.

It is here suggested that the Cormorant Formation (Deegan & Scull 1977; Cameron 1993) be abandoned and that undifferentiated strata be assigned to the Hegre Group. As far as there are formations within the Hegre Group, which covers the entire extent of those undetermined sections, it is suggested that the unassigned intervals should be provisionally assigned to the Hegre Group rather than to a certain formation of unassigned strata (Salvador pers comm).

The Judy, Julius, Joanne, Jonathan, Josephine and Joshua members erected by Goldsmith et al. (1995), are published both with and without lithologic terms included in the name (Cameron 1993; Goldsmith et al. 2003). It is preferable not to use both a lithologic term (mudstone, sandstone) and a unit term in the name of a lithostratigraphic unit (Salvador 1994). For this reason, lithologic terms in the Judy, Julius, Joanne, Jonathan, Josephine and Joshua members shall be excluded. In the lithostratigraphic schemes where they were originally published (Goldsmith et al. 1995) there are no lithologic terms in their names.

Smith Bank Formation

The Smith Bank Formation was originally defined by Deegan & Scull (1977) and has later been revised by Cameron (1993). Work by Goldsmith et al. (1995) has shown that the Smith Bank Formation is limited to the Early Triassic in the central North Sea area.

Well GB 30/12B-3 (Fig.6) shows a major two-fold subdivision of the Triassic. Goldsmith et al. (1995) defined the lower mudstone unit of this well as the Smith Bank Formation. The mudstone intervals of the upper succession are time-equivalent to the Alke and Skagerrak formations as these are known from the central North Sea. This conclusion is based on the fact that dating has shown that the lower unit is of Scythian (Induan-Olenekian) age, while the upper unit is of Middle and Late Triassic age (Goldsmith et al. 1995).

A 100 m thick mudstone (claystone) interval above the marginal marine facies of the Zechstein Group of well NO 17/12-1 (Fig.6) is defined as the Smith Bank Formation. This is based on its position immediately above the Zechstein Group, as well as a sparse microflora of Late Perman palynomorphs from beds which overly

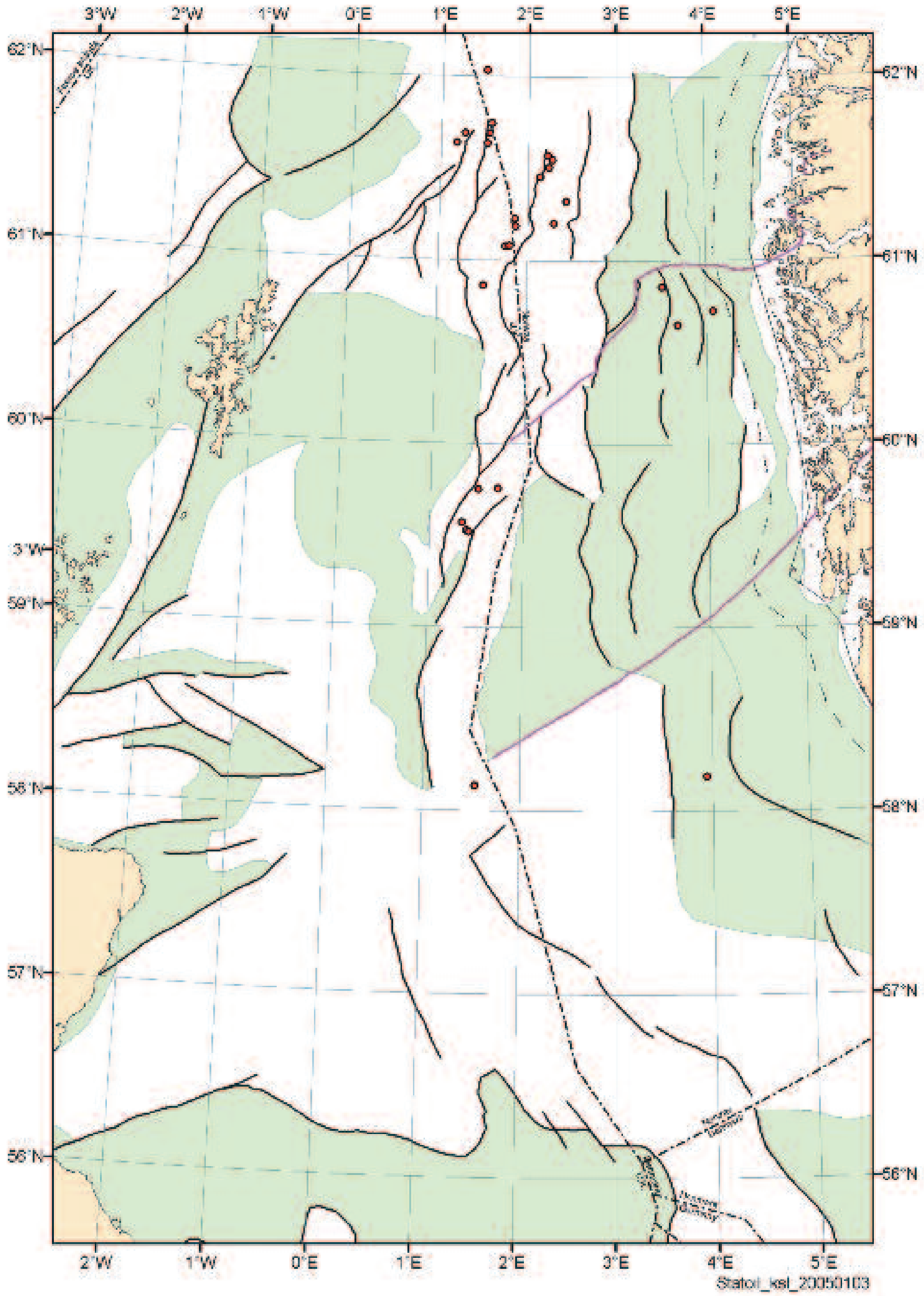

Fig. 9. Distribution of the Lomvi Formation.

Zechstein deposits (Lervik et al. 1989). The Triassic mudstone interval of well NO 17/3-1 may be subdivided into two units. The lower unit is interpreted as the Smith Bank Formation while the upper is interpreted as the Alke Formation.

The Smith Bank Formation has not previously been extended to the northernmost part of the northern North Sea, but it is here demonstrated that the formation should be extended to the northernmost part of the Northern North Sea Basin.

No deep wells have been drilled in the area between NO 17/3-1 and NO 31/6-1, but the Smith Bank Formation is recognized in the northern part of the northern North Sea. The 274 m thick massive mudstone interval lying on basement rocks in well 31/6-1 was dated as Early Triassic by Lervik at al. (1989). This mudstone interval is interpreted to represent the Smith Bank Formation. In the north eastern part of the northern North Sea Basin there are no Permian evaporites, and the Smith Bank Formation rests unconformably on older strata or basement rocks.

Microfloras reported from a mudstone interval at the base of the succession in well NO 33/5-1 indicate an Early Triassic (Scythian; Induan-Olenekian) age, while a Permian age, but post-Zechstein, was assigned to an approximately 100 m thick mudstone interval in well GB 210/4-1 (Lervik et al. 1989). Both those intervals are assigned to the Smith Bank Formation.

Lervik et al. (1989) defined two Triassic mudstone intervals (units I and IV) which were both correlated to the Smith Bank Formation. Unit I is here defined to be correlative with the Smith Bank Formation, based on microfloras and palynology as well as on the stratigraphical position of the unit. In addition to wells NO 33/5-1 and GB 210/4-1, wells NO 31/6-1, NO 34/4-4 as well as GB 211/7a-2 are interpreted to have the Smith Bank Formation in their succession. Well NO 32/4-1T2 also penetrated a mudstone interval in a position similar to well NO 31/6-1 This mudstone interval is therefore assigned to the Smith Bank Formation.

The central North Sea area has undergone extensive post-Triassic uplift and salt tectonics. This has added to the difficulties in recognizing which part of the Triassic succession has been penetrated when only mudstones are encountered. Certain wells have reached their total depths in the Smith Bank Formation, while others have total depths in the Alke Formation. Without the entire succession, including the Lomvi and Teist formations, the similarities between the Smith Bank and the Alke formations make it impossible to decide to which unit the mudstone facies belong.

Teist Formation

The Teist Formation (Vollset & Doré 1984) is characterized by a generally continuous interchange of red sandstones and mudstones. The thickness of the individual sandstone bodies averages only a few meters (Fig.5).Vollset & Doré (1984) indicated an Early to Late Triassic age for the sedimentary succession of the Teist Formation.

Only seven wells have short-cored sections of the Teist Formation. This limits our understanding of the depositional environment that the formation represents. More drilled sections and cores are needed to confidently interpret its depositional environment. The distribution of the Teist Formation is shown in Fig. 8.

Lomvi Formation

The Lomvi Formation was originally defined by Vollset & Doré (1984). Few wells had penetrated the formation at the time at which it was defined. The formation was described as a more than a hundred meters thick, blocky, massive, fine- to coarse-grained kaolinitic sandstone, with subordinate and thin red marls and claystones based on well information from the northern part of the northern North Sea. Recent wells have confirmed the nature of the original lithology, as well as the very distinct blocky pattern compared to under- and overlying strata. In the Beryl Basin, however, the formation shows a different pattern. The blocky pattern is dominant in the lower part, but a high proportion of interbedded sandstone and shale reflects a more erratic pattern in the upper part (Well GB 9/13a-22). Fig.9 shows the distribution of the Formation. The formation has a rather uniform thickness where it has been penetrated.

Cameron (1993) excluded the formation from the Triassic succession in the UK sector, claiming the formation was not observed in this part of the basin. Several wells, however, show the presence of the formation in the UK sector: 211/8A-2, 211/11B-4, 211/21-2, 211/7A-2RE and wells in the Beryl Basin (Frostick et al. 1992).

The formation has been dated as Scythian (Induan-Olenekian) to Anisian in well NO 34/4-4 and Ladinian in NO 31/2-4 by Lervik et al. (1989). Fisher & Mudge (1990) suggested the Lomvi Formation to be of Ladinian age.

Vollset & Doré (1984) interpreted the Lomvi Formation to have a fluvial origin. Nystuen et al. (1989) discussed the presence of very well rounded sand grains in the Lomvi Formation, concluding that aeolian facies or reworked aeolian deposits may be present in the formation.

Alke Formation

In the Statfjord Field area there is a 300 m thick basal mudstone interval, previously ascribed to the Lunde Formation (well NO 33/12-2) (Fig.5), which, however, was suggested upon definition by Vollset & Doré (1984) as a separate formation at a later stage. Lervik et al. (1989) elevated the thick, basal mudstone of the Lunde Formation to informal formation status. This interval is here separated out from the Lunde Formation and given formal formation status: the Alke Formation. It represents the upper of the two Triassic fine-grained intervals observed elsewhere in the basin.

No wells with biostratigraphic control show the two Triassic mudstone units within the same succession. Well GB 30/12B-3, included in Goldsmith et al. (1995), allows good biostratigraphic control. Above the Smith Bank Formation at 4525 m (14845 feet) there is an intercalation of sandstones and mudstones of Middle to Late Triassic age. This pattern is here interpreted as the advancing and retreating of the Skagerrak Formation in the distal parts of deposition in its progradation from the Fennoscandian Shield towards the southwest. The sandstone units are therefore parts of the Skager-

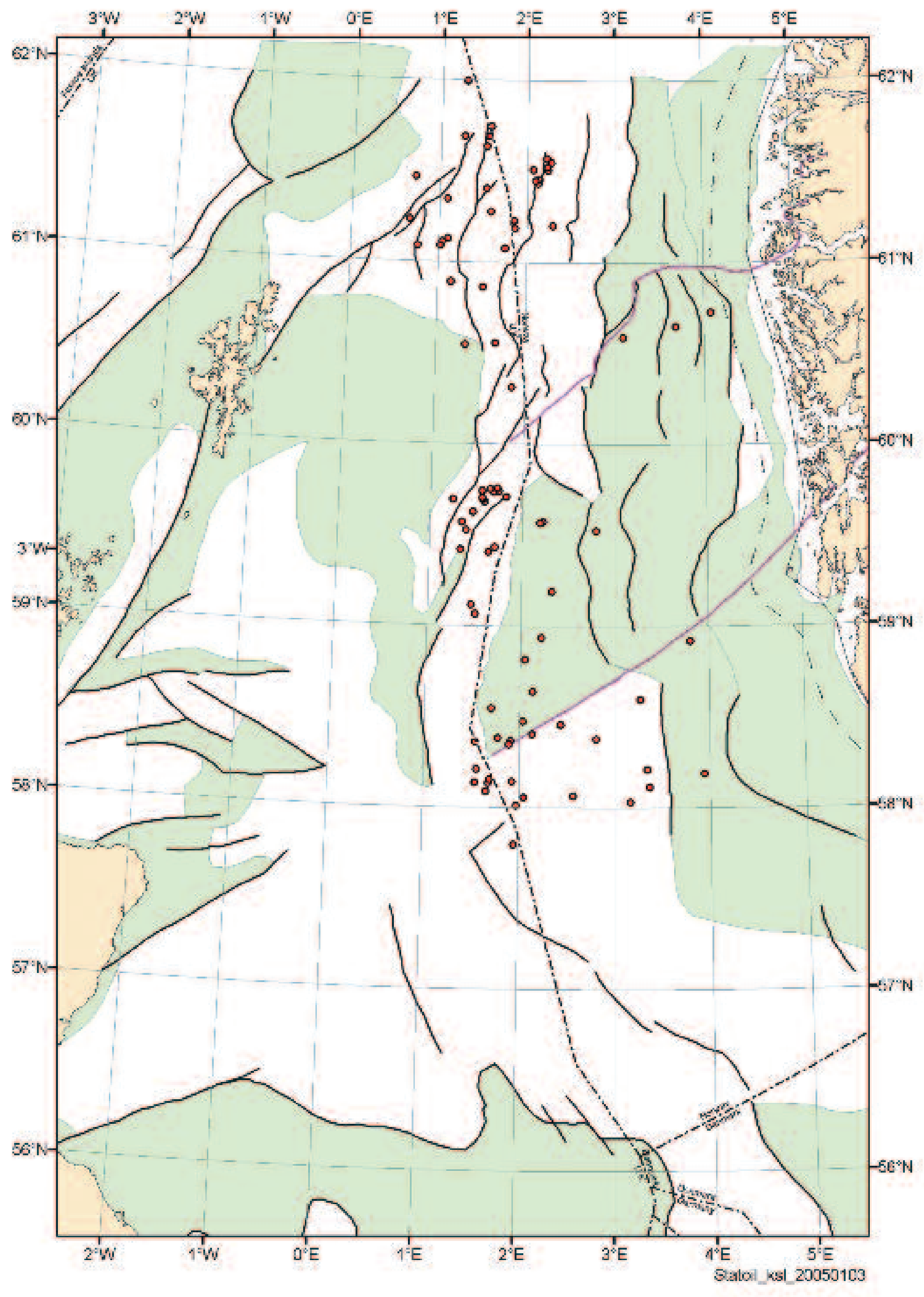

Fig. 10. Distribution of the Alke Formation.

rak Formation, while the mudstone units would represent the Alke Formation or the Smith Bank Formation. According to the descriptions given, all the fine-grained intervals between the sand prone intervals are mudstone-dominated and contain mainly non-evap-orate facies, which is in accordance with the lithology of the type well for the Alke Formation.

No sandstone of the Skagerrak Formation reached the Basin further south and west, leaving a continuous succession of mudstone within the Triassic, comprising the Smith Bank and Alke formations.

The two-fold division is also observed in other wells (NO 15/12-13, 17/3-1, 17/11-1). In proximal areas, the Smith Bank and Alke formations are separated by sandstones of the Teist and Lomvi formations.

The Alke Formation consists generally of a monotonous succession of mudstone, somewhat silty claystones. The mudstones and claystones are generally brick red, but in the area of the Snorre Field (Blocks NO 34/7 and 34/4) the uppermost part of the Alke Formation, previously, informally named the "middle Lunde member" of the Lunde Formation is characteristically greyish (Morad et al. 1998). In the Snorre Field, the Alke Formation is informally named "middle and lower members of the Lunde Formation", and is, in certain intervals, dominated by sandstone lithology, in particular the "lower Lunde member". The lower part of the Alke Formation interval of well GB 211/13-1 is also dominated by sandstone lithology. This succession is indicated as unit A (Fig. 5). More information is needed in order to understand the presence of sandstone within the Alke Formation interval. It is not rational to introduce sub-units within the Alke Formation at this stage, although the Formation is clearly two-fold in the Snorre Field.

Owing to the oxidised nature of the sediments, diagnostic floral suites are uncommon, resulting in poor time-stratigraphic control, which imposes limits on chronostratigraphical control.

Triassic mudstones are present over large parts of the Northern North Sea Basin (Fig. 7 and 10). The greatest thicknesses follow the present graben system, with more than five hundred meters in the Moray Firth Basin/Central Trough. Such great thicknesses of the mud-prone succession reflect a continuous succession of the Smith Bank and Alke formations. Very few of the wells show continuous successions with underlying and overlying strata due either to their not being completely pen-etrated or to eroded upper sections.

In the area of the Sleipner Field mudstone intervals are located directly on top of Zechstein deposits and succeeded by the Mid-Late Triassic Skagerrak Formation. Generally, where mudstone intervals lie directly above the Zechstein strata, it is most likely Smith Bank Formation. As the Utsira High has been interpreted to have been a local high area in pre-Triassic time (Færseth 1996), it is possible that the Utsira High was not buried until the Middle Triassic. Therefore, the mudstones between the Zech-stein Group and the Skagerrak Formation on the Utsira High may represent the Alke Formation. If there is not enough succession to define to which unit a certain part of the succession belongs, unspecified strata should be assigned to undifferentiated Hegre Group.

Skagerrak and Lunde formations

The Skagerrak Formation was originally defined by Deegan & Scull (1977) and described as consisting of interbedded conglomerates, sandstones, siltstones and shales. The age was assumed to be Middle and Late Triassic, but in areas of maximum development possibly as early as Early Triassic. The distribution of the Formation is shown in Fig. 11.

The Skagerrak Formation was defined at a time when few wells had penetrated the sedimentary succession in the western Skagerrak. All sandstone intervals in this region have been lumped into the Skagerrak Formation. It is clear that the Lower Triassic lithostratigraphy of the southern North Sea can be correlated as far north as the Egersund Sub-Basin (Bertelsen 1980). It is therefore possible that intervals mis-defined as being the Skagerrak Formation in certain wells in the Egersund Sub-Basin may represent strata corresponding to the age put to the Bunter Sandstone Formation. Several of the earliest wells of the Egersund sub-basin have completion logs, in which southern North Sea nomenclature has been used. Jakobsson et al. (1980) used the southern North Sea nomenclature for at least parts of the succession of well NO 17/12-1. After the introduction of the Skagerrak Formation, all Triassic sandstone intervals were lumped into this unit. A 152 meter thick Bunter Sandstone Formation interval has been defined in well DK 5708/18-1. The understanding of the Triassic strata close to the Fennoscandian Shield in the area north and south of the Norwegian - Danish border is poor. This is due to well successions with no age diagnostic criteria and no or very limited core material.

The deposits of the Skagerrak Formation were laid down in alluvial fan and fluvial environments (Deegan & Scull 1977).

It is clear that there is a difference in depositional regime from NO 17/12-1 to GB 30/12B-3 and GB 29/19-1A. (Fig.5). The lithological column of NO 17/12-1 is influenced by input from the Fennoscandian Shield while the column in the wells further west is, as discussed by Goldsmith et al. (1995), influenced by distal floodplain processes and marine incursions related to the Muschelkalk transgressions from the southern North Sea. The column of NO 17/12-1 is very similar to the columns of wells further north (Fig. 5 and 6).

While the Skagerrak Formation was defined in the southern area where sediments were supplied from the Fennoscandian Shield, the Lunde Formation was defined in the northern part. It would have been natural to have only one formation describing the sandstones, which have been shed off the Fennoscandian Shield in Middle to Late Triassic as there are no major differences in the sandstones of the Skagerrak and Lunde formations.

The Lunde Formation shows a succession of very fine to very coarse-grained sandstones, claystones, marls and shales. As mentioned under discussion of the Alke Formation, the lower claystone unit has been excluded from the Lunde Formation and assigned to the Alke

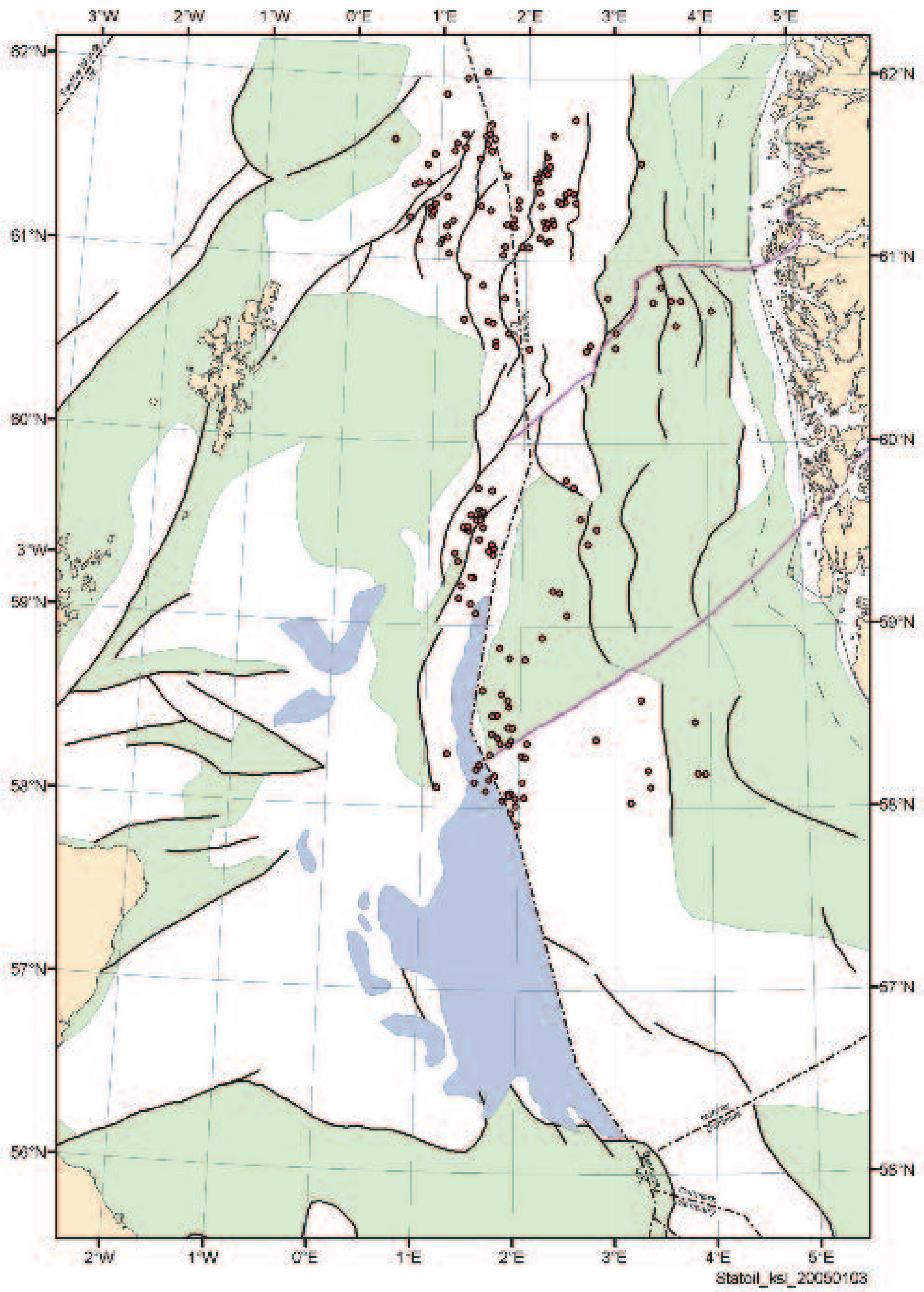

Fig. 10. Distribution of the Skagerrak and Lunde formations. The blue outline is from Cameron (1993) and shows the distribution of the Skagerrak Formation in the UK.

Formation. The Lunde Formation has therefore been adjusted from its original definition. As the lower boundary is changed, the Lunde Formation name should have been abandoned and the Formation should be redefined (Nystuen 1989). A revision of the Formation is presented in the appendix together with arguments for keeping the original name of the Formation.

The Triassic lithostratigraphical revision of Vollset & Doré (1984) included only the northern part of the northern North Sea. The Lunde Formation is therefore restricted to this area. The distribution of the Formation is shown in Fig. 11.

The age of the Lunde Formation is Late Triassic, possibly Norian to Early Rhaetian. As both the Lunde and Skagerrak formations are interpreted as responses to the same tectonic uplift of the Fennoscandian Shield, their ages should be approximately the same.

Deposition of the Lunde Formation is considered to have taken place in lacustrine or fluvial environments (Vollset & Doré 1984). According to Eide (1989), the lower part of the Lunde Formation was deposited in lacustrine or brackish water environments.

Since the Lunde Formation was defined by Vollset & Doré (1984), several authors have subdivided the Lunde Formation into sub-units (Nystuen et al. 1989; Steel & Ryseth 1990; Nystuen & Fælt 1995; Frostick et al. 1992). An informal three-fold sub-division into lower, middle and upper members of the Lunde Formation has been widely used. Those sub-divisions are related to reservoir and sequence stratigraphic sub-divisions rather than being of lithostratigraphic importance.

Where not exposed to extensive Cretaceous erosion, the Lunde and Skagerrak formations are succeeded by continuous sedimentation of the Statfjord and Gassum formations, respectively. The boundaries to these formations are dis-puted, as there is no distinct lithological break defining a clear boundaty between underlying and overlying strata.

A summary of the lithostratigraphy from selected sub-basins is given in Fig. 12.

Statfjord Group

In order to complete the Triassic succession, the Statfjord Formation should be included here as the lower part of the Statford Group (Deegan & Scull 1977) The Formation is of Rhætian age.

Vollset & Doré (1984) emphasized that the subdivision of the Statfjord Formation could only be applied west of the Viking Graben. It was concluded, based on the limited amount of wells drilled, that it was at that time premature to elevate the unit to group status. Many wells have penetrated the Statfjord Formation, both east and west of the Viking Graben since 1984. Several papers have showed that subdivision of the Statfjord Formation can be proposed with confidence (Nystuen & Fælt 1995; Ryseth 2001).

Cameron (1993) revised the Statfjord Formation by removing the Nansen Member from the Statfjord Formation, and assigned a Statfjord Formation and Nansen Formation to the Banks Group. According to international recommendations it is not possible to use the old name (Statfjord Formation) for a different unit (Salvador 1994; Nystuen 1989). Also, it is not possible to redefine a unit without the same information as is required for proposing a new unit. Change in rank of a stratigraphic unit, however, does not require redefinition of the unit or its boundaries (Salvador 1994; Nystuen 1989). Therefore the Statfjord Formation, as originally defined by Deegan & Scull (1977), is here upgraded to group status. The Raude, Nansen and Eiriksson members of the unit are upgraded to formations without any internal change in position and rank of the units (Fig. 12).

The boundary between the Statfjord Group and the Hegre Group is placed at the turning point of a fining-upward mega-sequence of the Lunde Formation with the coarsening-upward sequence of the Statfjord Group. This very often coincides with a sudden upward decrease of sonic log velocity.

It is rational to give the Statfjord Formation group status, as the succession represents a major part of the infilling of the North Sea Basin. Similar parts of the overall basin fill succession have group status (Hegre, Dunlin and Brent groups).

A major revision of the Statfjord Formation is possibly plausible, but only after comprehensive work including the entire northern North Sea, independent of national borders.

Appendix

Lithostratigraphic units in the northern North Sea, which have been defined previously or have not been revised, are not described here. For those units please refer to their original definitions.

The description of lithostratigraphic units given here is a revision of the description of Triassic units of Vollset & Dorè (1984) as well as a description of the Alke Formation, which is formally defined here.

Hegre Group

Name:
Named after the bird Heron (Norwegian: hegre).

Type area:
The type area is the northern part of the northern North Sea. The following wells are used to illustrate the Group: NO 31/6-1, NO 34/4-4, NO 33/12-5 (Fig. 5).

Thickness:
The Hegre Group is thickest in the eastern part of the basin where major subsidence occurred along the present Norwegian coastline. More than 2 km of Triassic sediments have been penetrated in the east (well NO 31/6-1). The Group thins towards the west in the northernmost part of the northern North Sea, while in the southern part (Central Trough and Moray Firth) substantial thicknesses are recognized. There might have been depositional systems along the East Shetland Platform during deposition of the Hegre Group, as great thicknesses of unspecified Triassic strata have been drilled here (see Comments below)

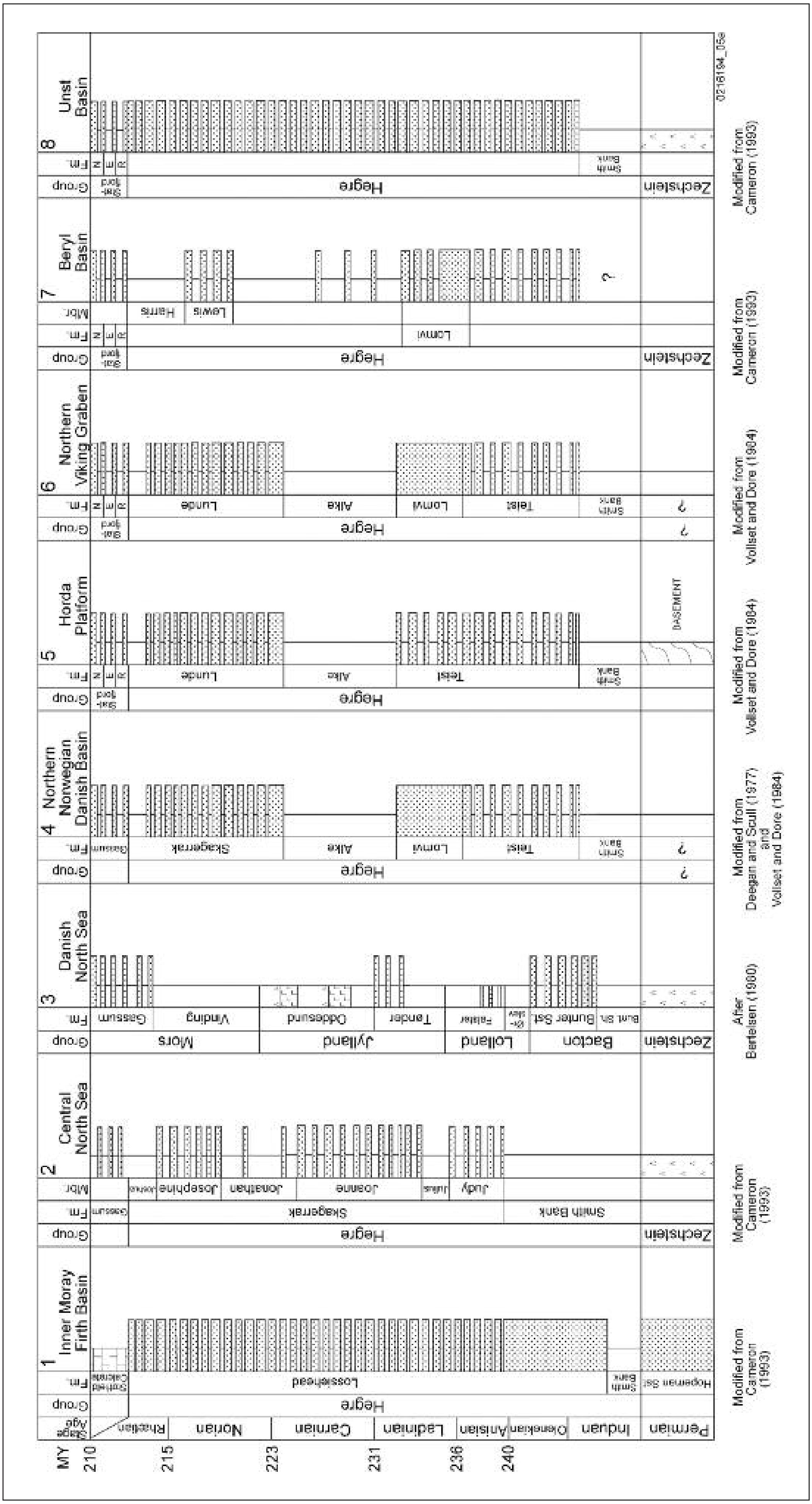

Fig. 12a. Triassic lithostratigraphy for the Northern North Sea Basin. R, E and N, as formations for the Statfjord Group, are the Raude, Eiriksson and Nansen formations respectively.

Lithology:
The Hegre Group consists of intervals of interbedded sandstone, claystones, mudstones and shales associated with sequences of dominantly sandstone or shale/claystone. The shales and claystones/mudstones usually have reddish colours whereas the sandstones show a range in colour from white, light grey, orange to brick red. The grain size varies from very fine to very coarse and the sediments are in parts of a pebbly nature. The Hegre Group also has intervals of white limestone, anhydrite and brownish-red marl.

Boundaries:
The base of the Hegre Group represents, in the southern and central parts of the northern North Sea, a transition from Zechstein carbonates and evaporites to Triassic silica-clastics. It represents a transition from high gamma and sonic readings of the carbonate-dominated Zechstein facies to the low gamma and sonic readings of the Smith Bank Formation. It is uncertain which wells show a continuous succession of Permian to Triassic siliciclastics, as the lower boundary is generally not detectable, as it represents a continuous succession of Rotliegendes red beds to Triassic sediments of similar characteristics. The Rotliegendes as well as the Triassic successions are generally barren of age diagnostic taxa. In the northernmost part of the Basin where Zechstein facies are absent, the base of the Hegre Group represents a disconformity to Caledonian basement (well NO 31/6-1).

Distribution:
The distribution of the Group is shown in Fig. 2 or Fig. 7 – 11. Fig. 2 shows wells of Triassic strata, which are the Hegre Group.

Comments:
The areas close to the margin of the East Shetland Platform and to the margin of the present Norwegian mainland generally show a succession of sandstones and mudstones. A succession (of a well) which does not show a complete Triassic succession, making it possible to subdivide it based on the overall lithostratigraphic pattern and totally absence of age diagnostic material, makes it very difficult or impossible to decide to which Triassic unit the sediments belong. The actual succession should therefore be assigned, unspecified, to the Hegre Group.

While the term Cormorant Formation (Vollset & Doré, 1984) was applied only to certain areas where a subdivision of the Triassic is impossible, it is suggested here that unspecified Triassic strata should generally be assigned to undifferentiated Hegre Group rather than to a formation of unspecified strata. The term Cormorant Formation should therefore be abandoned.

Teist Formation

Name:
Named after the bird Black Guillemot (Norwegian: teist).

Well type section:
NO 31/6-1 from 3455m to 3739 m, coordinates N 60° 38' 44, 89''; E 3° 40' 52, 28'' (Fig.5).

Well reference section:
Norwegian well 33/5-1 from 3298m to TD 3800m, coordinates N 61° 44' 46,10”; E 01° 34’47,40”

Thickness:
284 m in the type well and 502 m in the reference well.

Lithology:
The Teist Formation consists of interbedded sandstone, claystone, mudstone and marl. The sandstones are dominantly very fine- to fine-grained, dark red brown and calcareous.The sandstones of core cut of this formation in well GB 211/13-1 are well-sorted, medium- to coarse-grained, sub-angular to sub-rounded sand grains. The claystone and mudstone are red-brown while the marl is red-brown to white.

Boundaries:
The lower boundary represents a transition from the fine-grained lithology of the Smith Bank Formation to the sandstone prone lithology of the Teist Formation. This transition is characterized by a sudden decrease in the gamma ray readings - from generally high readings in the Smith Bank Formation to the irregular but generally average lower readings in the Teist Formation.

Distribution:
The distribution is showed on Fig. 8.

Age
Scythian - Carnian (Lervik et al. 1989)

Depositional environment:
No diagnostic flora indicating in which depositional environment the sediments have been laid down have been observed so far within the succession of the Teist Formation. The sedimentary succession of core 5 in well GB 211/13-1 is interpreted to reflect the migrating character of ephemeral channels in a fluvial system.

Alke Formation (New)

Name:
Named after the bird Razorbill (Norwegian: alke).

Well type section:
NO 33/12-2 from 3749m to 4048m, coordinates N 61°13’31,38”; E 01°51’ 25,97”.

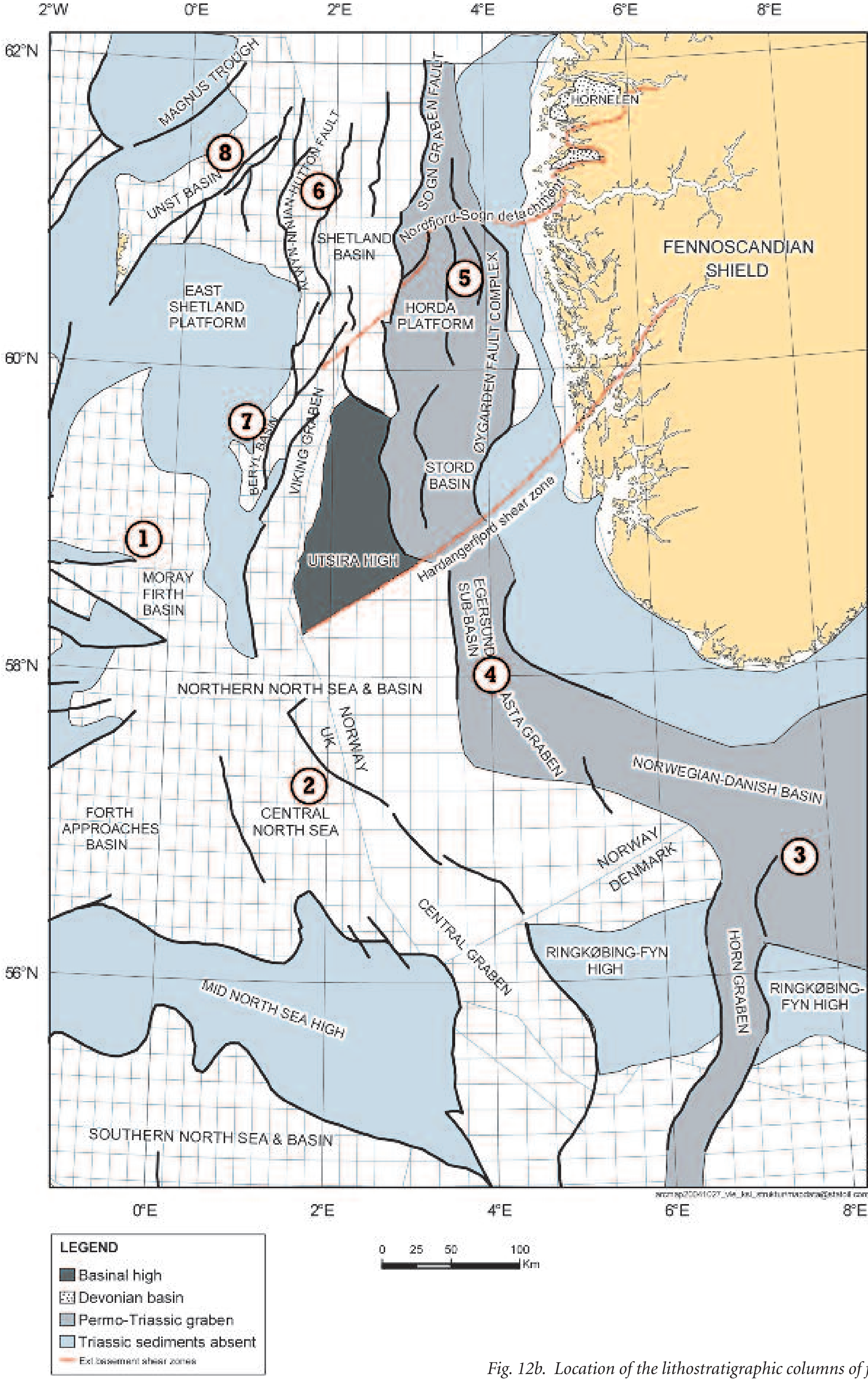

Fig. 12b. Location of the lithostratigraphic columns of figure 12a.

Well reference sections:
GB 211/29-5 from 3795m to 4055m, coordinates N 61°04' 43,00"; E 01°45'46,50".
NO 34/4-C-6H from 2980m to 3452m, coordinates N 61°31' 30,51"; E 02°12'40,66".

Thickness:
299m in the type well and 260m in the reference well.

Lithology:
The Alke Formation is dominated by brick red to red-brown, grey and grey-green claystones and mudstones as well as marls which are normally soft, silty and micaceous.

Boundaries:
The lower boundary represents a transition from the massive sandstones of the Lomvi Formation. This transition is very sharp, reflected by a sudden increase in the gamma ray log readings.

Distribution:
The distribution is showed on Fig.10.

Age:
Ladinian - Carnian

Depositional environment:
The clay- and mudstones of the Alke Formation are interpreted to be deposited distally to major proximal siliciclastic depositional systems.

Comments:
In the Snorre Field the interval of the Alke Formation is, in certain intervals dominated by sandstone lithology (the "lower Lunde member"). The lower part of the Alke Formation interval of well GB 211/13-1 is also dominated by sandstone lithologies. This succession is indicated as unit A (Fig. 5). More information is needed in order to understand the presence of sandstone within the Alke Formation interval. It is not rational to introduce sub-units within the Alke Formation at this stage.

Lunde Formation

Name:
Named after the bird Puffin (Norwegian: lunde)

Well type section:
NO 33/12-2 from 2951m to 3749m, coordinates N 61°13'31,38"; E 01°51' 25,97".

Well reference sections:
GB 211/29-5 from 3003m to 3795m, coordinates N 61°04' 43,00", E 01°45'46,50".
NO 34/4-C-6H from 2980m to 3452m, coordinates N 61°31' 30,51"; E 02°12'40,66".
NO 34/7-3 from 2635m to 3365m, coordinates N 61°25' 54,05"; E 02°07'43,95".

Thickness:
798m in the type well and 792 m in the reference well.

Lithology:
The succession of the Lunde Formation is dominated by very fine- to very coarse-grained sandstones, claystones, mudstones, shales and marls. The sandstones are mainly white while the fine-grained lithologies are generally red, green and grey-green. This contrasts to the pre- Alke Formation succession, in which all lithologies are generally red stained. Especially in the upper part of the succession the claystones and mudstones are non-stained.

Boundaries:
The base of the Formation is placed at the transition from the fine-grained lithology of the Alke Formation to the intercalated sandstones and mudstones/claystones of the Lunde Formation. This transition is marked by a distinct change in the sonic and gamma ray logs.

Distribution:
The distribution is shown on Fig. 11. The distribution of the Lunde Formation of this figure is north of 60 degrees.

Age:
Late Triassic, Norian to Early Rhaetian.

Depositional environment:
The Lunde Formation represents a major depositional fluvial system, building out from the Fennoscandian Shield, or/and from the East Shetland Platform.

Comments:
The base boundary of the Lunde formation has been changed from its original definition. It was, at the time of its original definition, discussed that the lower unit of the Formation should be erected and defined as a separate unit at a later stage (Vollset & Doré 1984). As the lower boundary has been changed, the Formation should have been abandoned and a new name erected. Salvador (1994), states, however, that units which have been in extensive use, can keep their original names even if the boundaries of the formation have been changed. Nystuen (1989) states that minor changes in the definition of boundaries may be desirable following new investigations. If such revisions only alter a small portion of the original unit, its name can be retained. The Lunde Formation is an important reservoir in the Snorre Field and the term has been extensively used. As it was already mentioned upon definition that the lower boundary of the formation should be modified, it is chosen here not to abandon the Formation, but rather to adjust its lower boundary. It is mainly the upper part of the Lunde Formation which has been dealt with as a reservoir within the Snorre Field, and it will therefore affect its use only to a minor degree.

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A Late Triassic dinosaur bone, offshore Norway

Jørn Harald Hurum, Morten Bergan, Reidar Müller Johan Petter Nystuen & Nicole Klein

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A section of bone is described from a well core retrieved from a depth of 2615 m in the Lunde Formation of the Snorre Oil Field, Norwegian North Sea. The specimen is interpreted to be the metaphyseal region of a limb bone showing radial fibro-lamellar tissue of a type described for *Plateosaurus* from the Late Triassic of Germany. Associated palynomorphs palynomorphs suggest the Norwegian specimen to be from the Early Rhaetian (ca. 202-203 Ma).

Jørn Harald Hurum, Natural history Museum, University of Oslo, P.O.Box 1172 Blindern, NO-0318 Oslo, Norway (j.h.hurum@nhm.uio.no); Morten Bergan, RWE-Dea, Karenslyst allé 2, Postboks 243 Skøyen, NO-0213 Oslo, Norway (Morten.Bergan@rwe.com); Reidar Müller and Johan Petter Nystuen, Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, NO-0316, Oslo, Norway (rm@forskningsradet.no; j.p.nystuen@geo.uio.no). Nicole Klein, Fachschaft Geologie/Paläontologie, Mathematisch-Naturwissenschaftliche Fakultät der Rheinischen Friedrich-Wilhelms-Universität. Nußallee 8, 53115 Bonn, Germany.

Introduction

Mesozoic reptiles are known from several localities on Svalbard and from one locality on the Norwegian mainland (Heintz 1964). The former are of Triassic and Jurassic age and include ichthyosaurs and Jurassic plesiosaurs. These are described in the early works by Hulke (1873) and Wiman (1914), but also from more recently work by Persson (1962) and Worsley & Heintz (1977) (for a historical review see Heintz 1964 and Nakrem et al. 2004). Dinosaur tracks are known from several Early Cretaceous localities on Spitsbergen (Lapparent 1960, 1962; Edwards et al. 1978). On the mainland one partially complete ichthyosaur has been described from the Late Jurassic of Andøya (Ørvig 1953; Dalland 1980; Nordborg et al. 1997). As a result of offshore drilling, several bone fragments of plesiosaurs and ichthyosaurs have been found in cores. However, these finds have only been summarily described (Heintz & Sæther 1999).

In 1997 a bone fragment was identified by M. Bergan and J.P. Nystuen in a core from the Snorre Field well 34/4-9S, in the Late Triassic Lunde Formation. The Snorre Field is located in the northern part of the Norwegian North Sea (offshore blocks 34/4 and 34/7; see Fig. 1).

Study of this bone fragment (PMO 207.207, PMO-Paleontological Museum, Oslo) forms the subject of this paper.

Geological framework

The Lunde Formation occurs in the northern part of a Late Triassic continental basin that covered most of the present North Sea area. Several thousands of meters of fluvial sediments were deposited in this basin during a thermal subsidence phase following Late Permian to Early Triassic rifting (Badley et al. 1988; Nystuen et al. 1989; Steel 1993; Nystuen & Fält 1995). With an approximate width of 400 kms between present mainland Norway and the Shetland Platform, the continental post-rift basin contains the Teist, Lomvi and Lunde formations, and lasted throughout the Triassic until the final depositional stages of the overlying latest Triassic – Early Jurassic Statfjord Formation, when the whole area was flooded during a marine transgression from the north and south in Late Sinemurian - Early Pliensbachian time (Nystuen & Fält 1995). The climate during deposition of the Lunde Formation was semi-arid and highly seasonal, typical for the contemporary palaeogeographic position at 40-50 degrees North latitude (Müller et al. 2004).

The basin was linked to a marine borealic seaway, probably located some 10's to 100's km to the north (Nystuen & Fält 1995) and to sediment source areas composed of Archaean gneisses, Caledonian metamorphic rocks and Devonian sandstones (Mearns et al. 1989; Nystuen & Fält 1995; Knudsen, 2001). These sources located on the Shetland Platform and in the SW part of Norway and shed out into a vast alluvial plain in the Triassic North Sea. The Snorre oil field is described in Jorde & Diesen (1992) and Bergan & Diesen (2002).

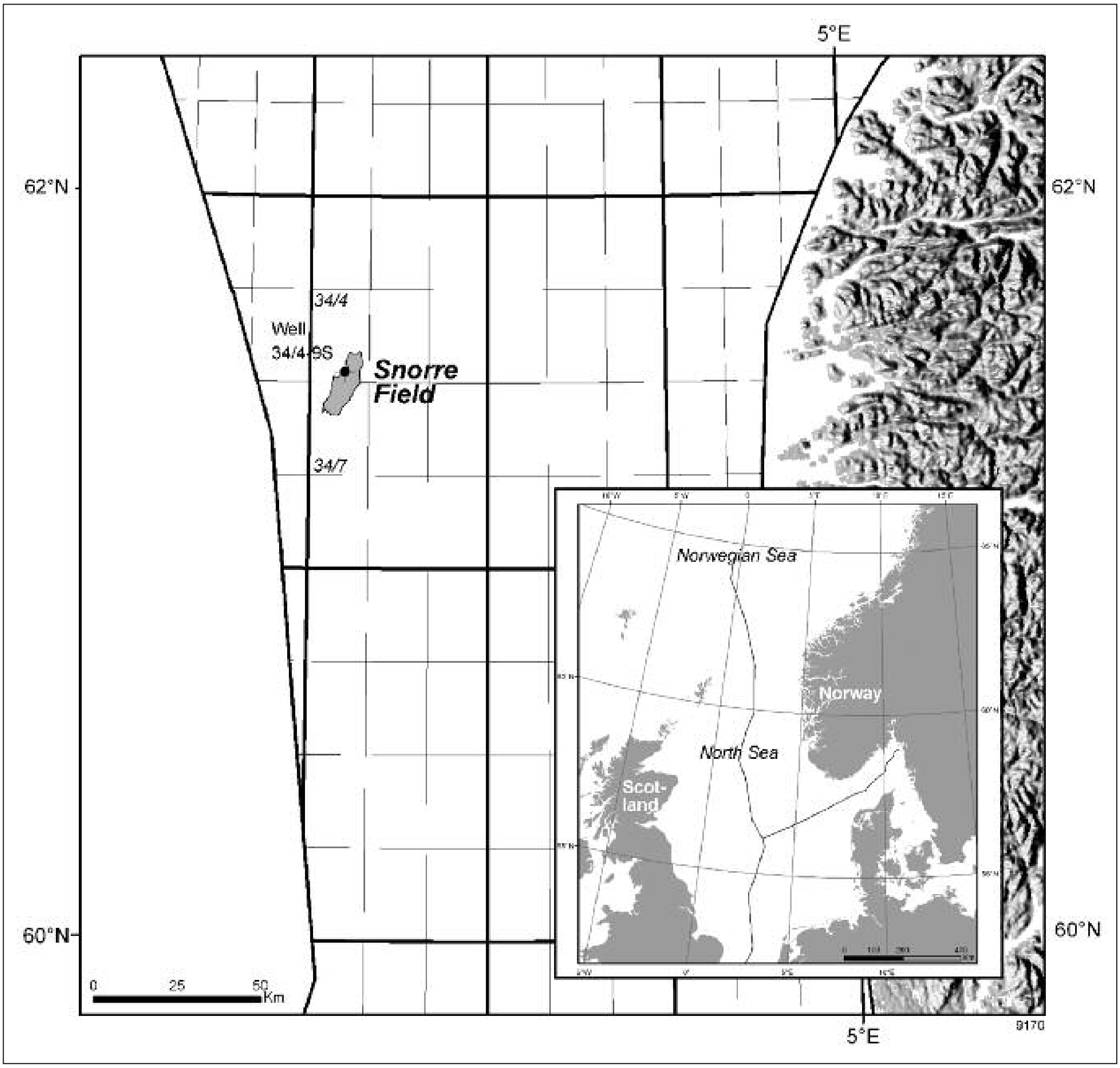
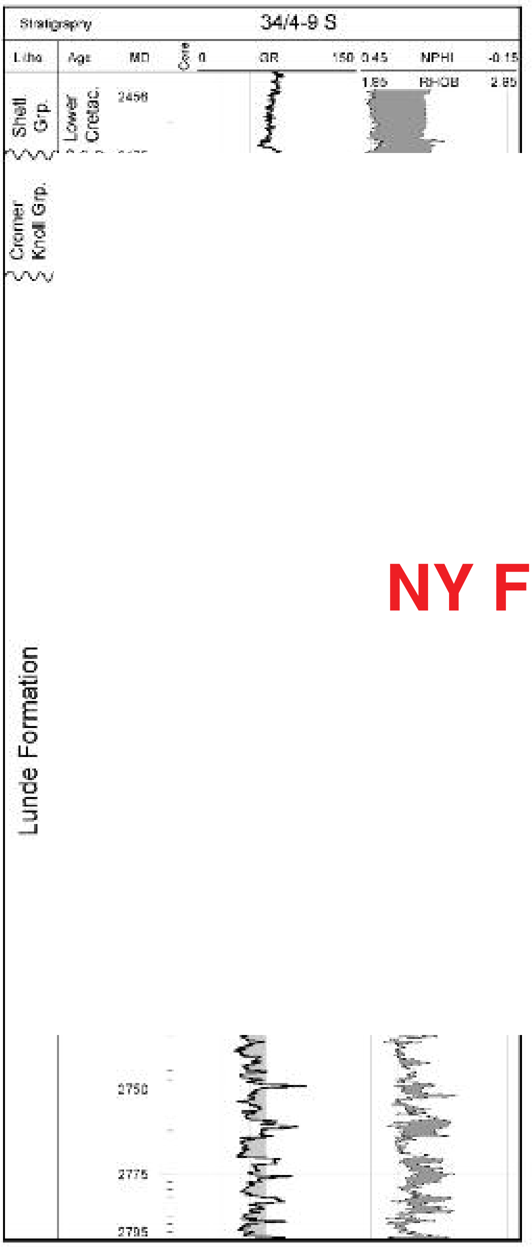


Fig. 1. Map of the area with Snorre well 34/4-9S location.

Location, depositional environment and age

The bone slice was discovered during the description of a core retrieved in February 1997 from well 34/4-9S in the north-western part of the Snorre Field (61°30'45"N and 2°10'18"E). It occurs in a reddish-brown, mudstone interval referred to as the upper member of the Lunde Formation (reservoir zone L03 ; cf. Diesen et al. 1995) (Fig. 2). The mudstone is composed of dominantly compound and cumulative paleosols that formed in distal to fluvial channels in a flood-plain forming the uppermost part of the upper member of the Lunde Formation (Müller 2003). The paleosols are characterized by carbonate nodules, pedogenic mud aggregates and slickensides, mottling, root traces and mud cracks. The paleosol type is similar to modern vertisols forming in semi-arid areas with seasonal precipitation, commonly with dry periods lasting 4-8 months (Dudal & Eswaran 1988; Driese & Mora 1993; Müller et al. 2004). The presence of root traces suggests that the flood-plain was covered with small trees and bushes, vegetation suitable for herbivorous animals living on the alluvial plain.

Beds containing the bone specimen belong to the younger of two palynomorph assemblages containing the spore *Kreuselisporites reissingeri* thought to indicate an early Rhaetian rather than a Norian age (Eide 1989), corresponding approximately to an age of 202-203Ma according to the time scale of Gradstein et al. (2005).



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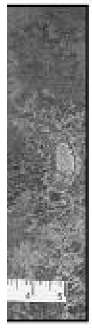

Fig. 2. Section of the sedimentological log from well 34/4-9S in the Snorre Field with the position of the bone shown in detail.

Histological description

The described specimen (PMO 207.207) has been slightly crushed but is clearly a cross section of a long bone. The bone is about 40 mm in diameter, well preserved and whitish to light grey in color. The medullary cavity lined with cancellous bone, and the cortical compacta or cortex, are both identifiable. The compact bone exhibits two different histological compositions, an inner dense tissue or fibro-lamellar bone and an outer more vascular part (Fig. 3). The fibro-lamellar bone is present in almost all dinosaurs and is a characteristic feature of fast growing animals. In thin sections it shows two lines of arrested growth (LAGs) in its outer part. The bone shows a relatively high vascular density and therefore represents fast growing bone tissue (Klein 2004). The osteons in the tissue are mostly rounded and primary. There are only a few known examples of remodeling with secondary osteons.

The outer zone of the bone is extremely vascular and is identical to what Klein (2004) called the radial fibro-lamellar bone tissue (RFB). This she describes as *"The bone tissue is still the fibro-lamellar complex, but the kind of vascularization is different. It consists of parallel radial vascular canals with a very high density. Although this bone type shows such a high vascularization, which indicates a very rapid growth rate, the tissue is deposited cyclically and delimited by normal lines of arrested growth. It occurs always in the outer cortex areas. Due to the predominance of radial vascular canals in this tissue, it is called in the following radial fibro-lamellar bone tissue (RFB)"* Klein (2004:53). The radial fibro-

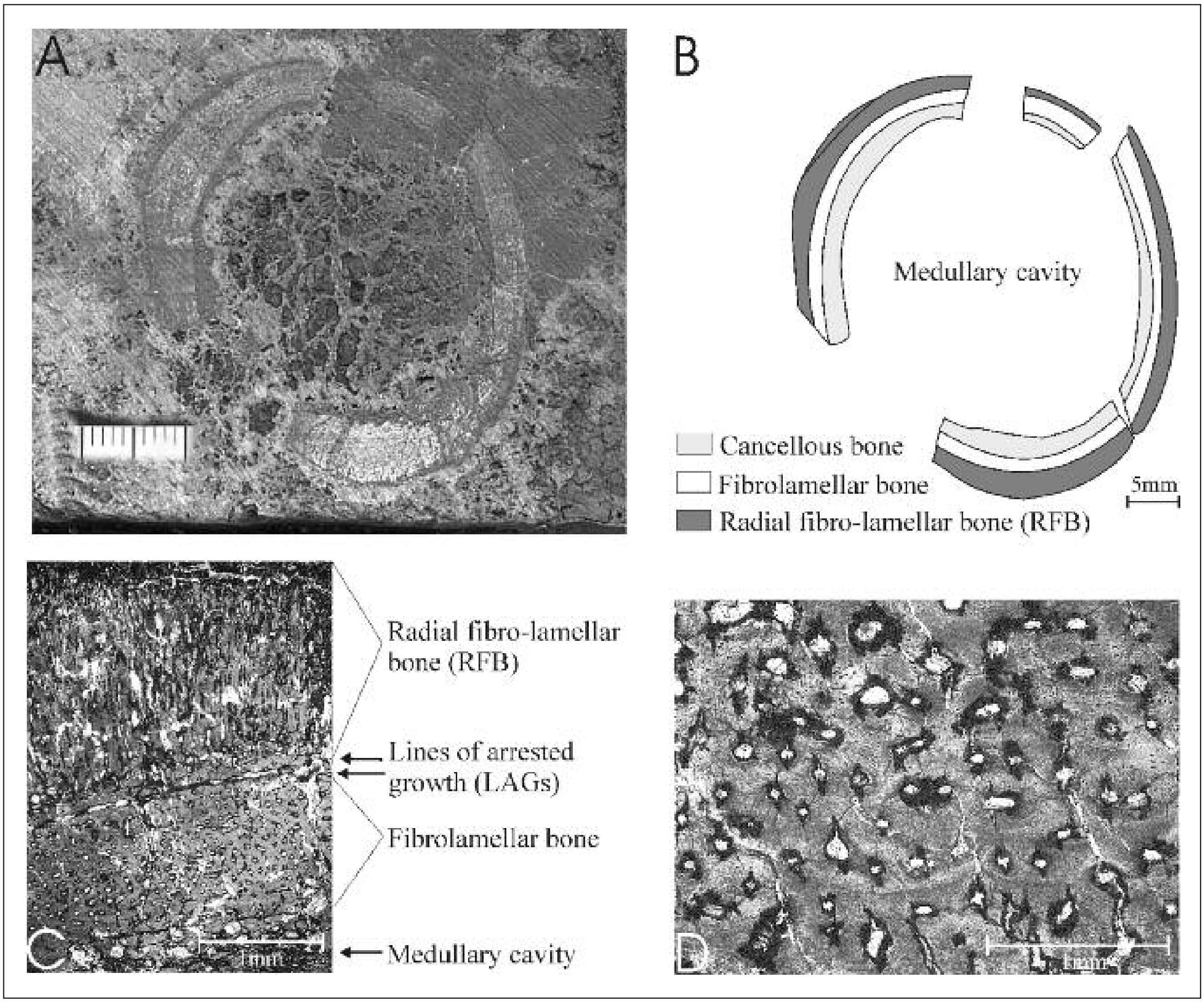

Fig. 3. Detail of bone found at 2615 meter in well 34/4-9S. B. Schematic drawing of section. C. Thin section of bone showing three different histologies. D. Detail of the fibro-lamellar bone, showing few secondary osteons.

lamellar bone tissue forms from a third to more than a half of the thickness of the Snorre Field bone in PMO 207.207. The very thin cortex suggests that the section is from the metaphyseal region of the bone, not the middle of the shaft.

Discussion

Histological studies of Triassic terrestrial tetrapods began with the work of Seitz (1907) and Gross (1934), whilst later dinosaur histology includes that on the prosauropods by Ricqlès (1968), Reid (1990), Chinsamy (1993a), and Klein (2004), the theropods by Chinsamy (1993b) and Starck & Chinsamy (2002) and the mammal-like reptiles by Ricqlès (1969) and Ray & Chinsamy (2004).

Fibro-lamellar bone tissue is very common in dinosaurs, birds and mammals but the radial fibro-lamellar bone tissue (RFB) seen in the thin sections is so far only described in two dinosaur genera. Klein (2004) described RFB in the tibia, femur, vertebra and ischium of the prosauropod *Plateosaurus engelhardti*, and it is associated with very rapid growth and high rates of bone deposition. Similar tissue (referred to as "highly porous radially vascularized bone") is also known from the Cretaceous ornithischian dinosaur *Psittacosaurus mongoliensis* (Erickson & Tumanova 2000). The terminology of Klein (2004) is followed here since the present bone histology can be directly compared with that figured by her (Klein 2004, figs. 3D,H).

The size of the bone fragment and general appearance causes us to interpret this as a prosauropod limb bone. Prosauropods are the most common dinosaurs of the Norian (Late Triassic) and are also important in the Early Jurassic. *Plateosaurus* is a fairly large and well known prosauropod dinosaur (adults about 6-10 m

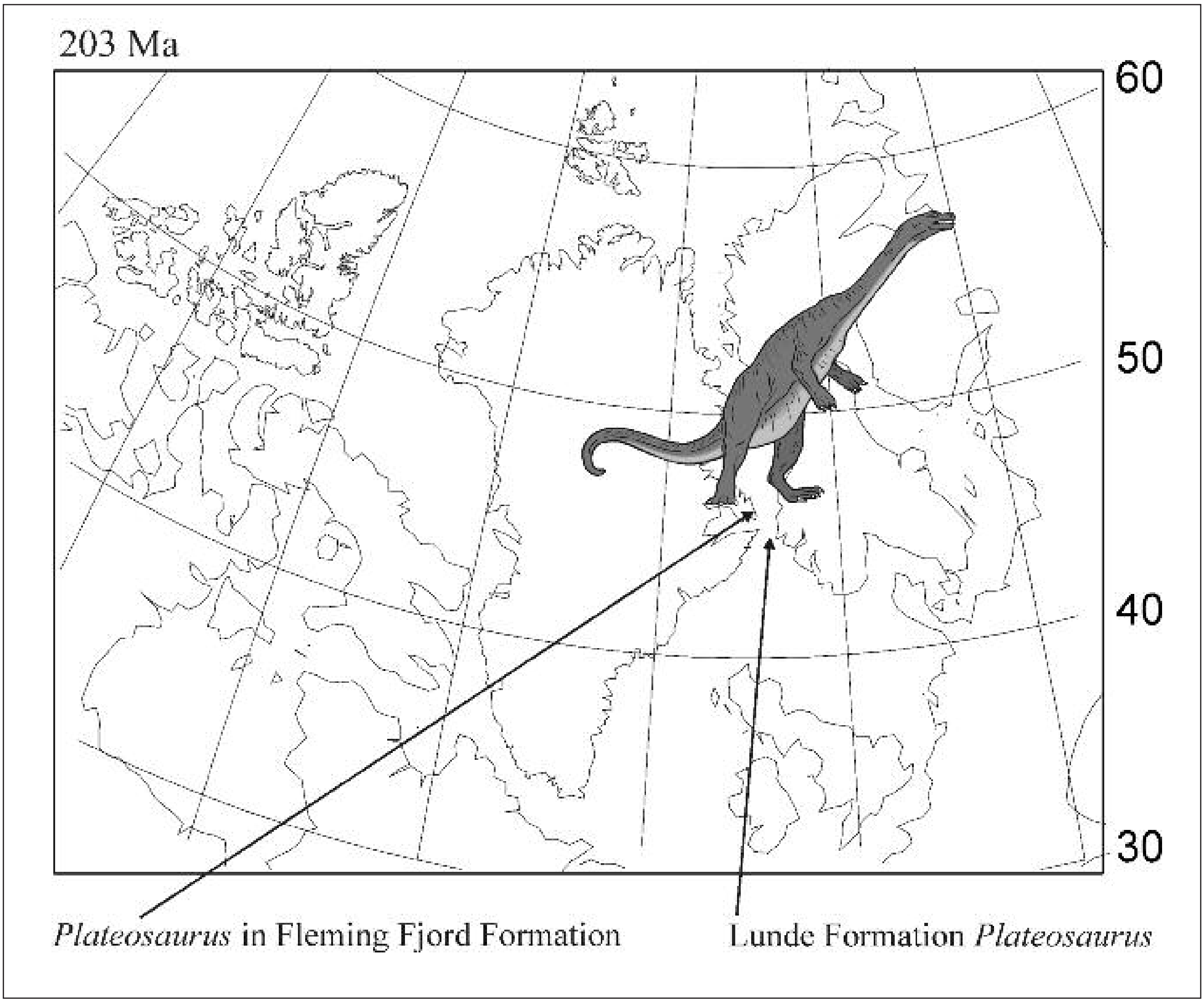

Fig. 4. Paleogeographic reconstruction showing the position of the Snorre Field and the East Greenland localities.

long). It was first described by von Meyer (1837) and has since become one of the best known early dinosaurs following excavations between 1911-1932 at Trossingen, near Tübingen, Germany (Sander 1992). These excavations uncovered a huge accumulation of articulated, partial to complete skeletons of this late Norian prosauropod. It was this material that Klein (2004) used to describe the histology of *Plateosaurus engelhardti*. Interestingly, the prosauropods are the first known high-browsing terrestrial herbivores (Galton & Upchurch 2004) and could have fed up to 4 meters above the ground (Galton 1986).

Correlation with other known terrestrial localities

Several famous terrestrial vertebrate localities of Norian to Rhaetian age are known around the world (Zawiskie 1986). In North America, Early - Middle Norian terrestrial faunas come from the middle Chinle Formation and Newark Supergroup, whilst in Germany they are known from the Keuper Stubensandstein and Knollenmergel. The faunas are somewhat provincial, but they have certain elements in common. The European localities contain an abundance of prosauropods (Sander 1992) and turtles, while the North American fauna is dominated by metoposaurs, phytosaurs and aetosaurs (Lucas 1998).

Late Norian to Rhaetain European faunas include a variety of sphenodontids and primitive mammals in addition to dinosaurs, crocodilomorphs, labyrinthodonts and thecodonts. The North American faunas are characterized by a relatively high abundance of theropod dinosaurs (Lucas 1998).

The closest terrestrial vertebrate localities to the Snorre Field, when palaeogeographical reconstructions are taken into consideration (Fig. 4), are those from Upper Triassic outcrops in East Greenland, such as the Fleming Fjord Formation (Jenkins et al. 1995). Here, the depositional environment is similar to that of the Lunde Formation. However, the biostratigraphy is uncertain and both invertebrates and palynomorphs only indicate that the formation spans most of the Carnian, Norian and Rhaetian. Jenkins et al. (1995) described a predominantly European assemblage containing Plateosaurus, theropods, turtles, mammals, aetosaurs, pterosaurs, labyrinthodont amphibians and fishes from the Ørsted Dal and Malmros Klint members of the Fleming Fjord Formation, and assigned the Ørsted Dal Member to be of Norian age based on the tetrapods. Lucas (1998) correlated this with the Stubensandstein of Germany.

Conclusion

The bone found in the Late Triassic upper member of the Lunde Formation in core from well 34/4-9S in the Snorre Field in the northern North Sea represents a prosauropod longbone. Although the assignment of the present material to the Early Rhaetian, based on pollen and spores is imprecise, the histology of the skeletal fragment is so like the German Norian material of the prosauropod dinosaur *Plateosaurus* that we assign it with confidence to this genus. This is the first find of any dinosaur bone from Norwegian territory.

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